IMPROVING LONG-TERM PRODUCTION DATA ANALYSIS USING ANALOGS TO PRESSURE TRANSIENT ANALYSIS TECHNIQUES

A Thesis

by

DAMOLA OKUNOLA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Petroleum Engineering

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Approved by:

Chair of Committee, Christine Ehlig-Economides
Committee Members, Yuefeng Sun
Peter P. Valko
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ABSTRACT

Improving Long-Term Production Data Analysis Using Analogs to Pressure Transient Analysis Techniques. (December 2008)

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Chair of Advisory Committee: Dr. Christine Ehlig-Economides

In practice today, pressure transient analysis (PTA) and production data analysis (PDA) are done separately and differently by different interpreters in different companies using different analysis techniques, different interpreter-dependent inputs, on pressure and production rate data from the same well, with different software packages. This has led to different analyses outputs and characterizations of the same reservoir. To avoid inconsistent results from different interpretations, this study presents a new way to integrate PTA and PDA on a single diagnostic plot to account for and see the early time and mid-time responses (from the transient tests) and late time (boundary affected/PSS) responses achievable with production analysis, on the same plot; thereby unifying short and long-term analyses and improving the reservoir characterization. The rate normalized pressure (RNP) technique was combined with conventional pressure build-up PTA technique. Data processing algorithms were formulated to improve plot presentation and a stepwise analysis procedure is presented to apply the new technique. The new technique is simple to use and the same conventional interpretation techniques as PTA apply. We have applied the technique to a simulated well case and two field cases. Finally, this new technique represents improvements over previous PDA methods and can help give a long term dynamic description of the well's drainage area.

DEDICATION

To my mother for your limitless love, courage, patience and belief in me. I have made it this far solely because of you. No words can express my gratitude to you.

To my siblings, Lara, Biodun, Folake, Dolapo, Fatima, Musty and Ajoke, you guys are too much, we are partners and you all mean the world to me;

To my very good friends; Afolabi, Funke, Yomi, Nyasha, Oye, Gbemi, Shelly, Kelley, Nike and Rasheed. College Station would have been a drab without you all. Thanks for all your support and friendship;

To my fellow graduate students, especially the Nigerians, with whom we shared failures and successes, sorrows and laughs, they say the sky is the limit – we won't stop there;

To my late father, my model Petroleum Engineer, and role model for life. Dude we miss you;

And to God, for His blessings in my life, making me the way I am, and the grace to surround me with my family and friends.

ACKNOWLEDGEMENTS

I would like to express my sincere gratitude and appreciation to my advisor, Dr. Christine Ehlig-Economides for her invaluable guidance and support through my studies at Texas A&M. Her motivation dedication and energy has influenced this period of my life.

I would also like to thank Dr. Peter Valko and Dr. Yeufeng Sun for serving as members of my graduate advisory committee.

Thank you Nike and Qingfeng; sharing ideas with you always brings new ideas and insights to problems.

And finally thank you to Esso Producing Nigeria for sponsoring my graduate studies at Texas A&M University.

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CHAPTER I

INTRODUCTION

Dynamic flow describes any intended or unintended flow process, during exploration or production operations, where movement or diffusion of fluid takes place within a reservoir. During dynamic flow between a reservoir and one or several wells, a transient response(s) can be recorded. This includes, but is not limited to, all types of well test operations, formation testing, and the actual reservoir production where permanent monitoring may record rates and pressures.

Dynamic flow analysis of dynamic flow is the process of handling and interpreting dynamic flow data in order to obtain information about the reservoir and/or wells. Dynamic flow analysis broadly includes pressure transient analysis (PTA) and production data analysis (PDA) as illustrated in Figure 1.1.

This thesis follows the style of *SPE Reservoir Evaluation and Engineering Journal.*

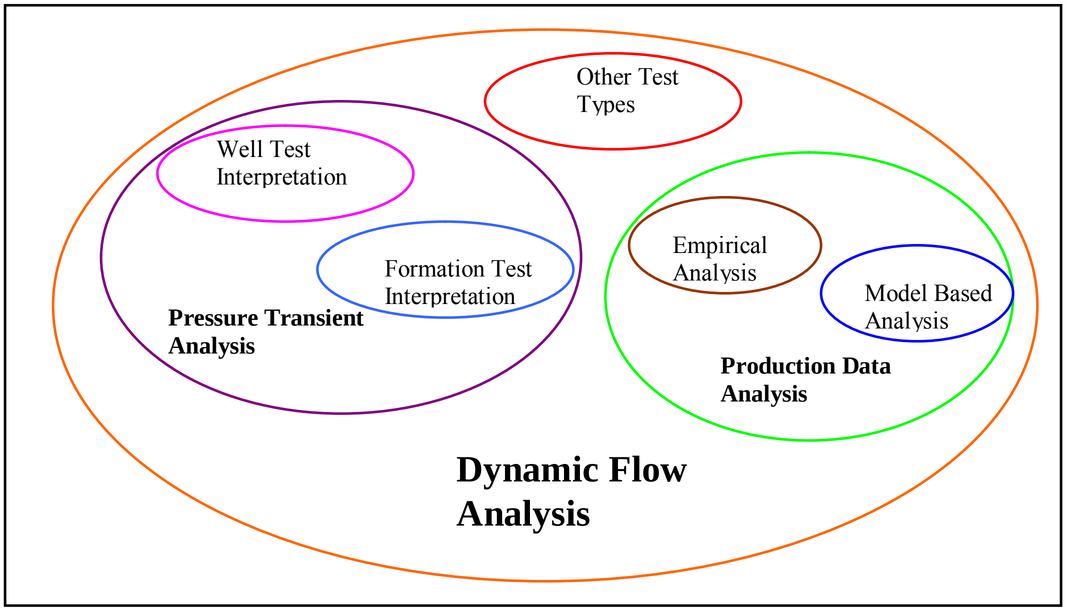

Figure 1.1: Dynamic Flow Analysis

PTA involves analysis of a segment of pressure data recorded while the well is producing at a constant rate, usually zero (shut in well). In most well tests, a limited amount of fluid is allowed to flow to or from the formation being tested, then the well is closed and the pressure is monitored while the fluid within the formation equilibrates. The analysis of the resulting transient pressure response can be used to characterize reservoir characteristics near the wellbore (such as skin, limited entry, vertical fracture) and more distant from the well (such as a fluid contact, mobility change, sealing or leaking bed or lateral boundaries).

For PTA, the rates from the tested well(s) are required and, where applicable and possible, it is helpful to have rate data for nearby wells. In addition the pressure response, preferably from downhole measurement, and generally acquired during build-ups is recorded. Additional required information includes the fluid physical properties; pressure, volume, temperature and possibly logs and geology. The basic requirement for pressure transient analyses is illustrated in Figure 1.2.

A rich model catalog based on the solution of the diffusivity equation satisfying appropriate boundary conditions exists for PTA. The time domain of interest for PTA is from a few seconds to a maximum of a few days.

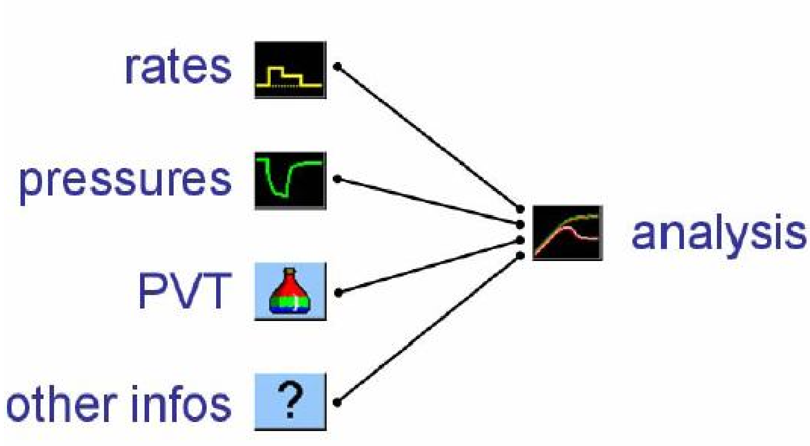

Figure 1.2: PTA and PDA Analysis Path[1]

The main objective for PDA has been to forecast long-term production. Production data is acquired for all wells, but often production from several wells is manifolded, and production from an individual well must be back-allocated. The well data collected typically include daily or weekly gas, water, and condensate volumes, and occasional shut-in pressures.

Oftentimes in green fields, the only data available for analysis of a well is its production data and possibly some basic well log information. Also the most common data that engineers can count on, especially in mature fields, is production data. The accuracy and availability of the hydrocarbon production data of a well is generally very good since (1) the oil and gas production represent revenue for the operator of the well, (2) the data is readily available from the operator's own production data base or from commercial production data services, and (3) most governmental regulatory agencies require accurate reporting of these values.

These data represent a source of information about the ongoing dynamic flow process in the reservoir. In some cases, rigorous analysis of these data can provide a reservoir characterization. With properly recorded wellhead flowing pressures and daily or monthly production data, PDA can be performed using the production data to convert the wellhead-recorded pressure and rate data to bottomhole flowing conditions while accounting for pressure losses in the downhole assembly. Alternatively, there may be pressure measurements recorded on a permanent gauge located near the production interval. Pressure and rate data can then be analyzed using rigorous reservoir inflow performance models to estimate reservoir and well properties.

Pressure transient tests have been used for many years to assess well conditions and obtain reservoir parameters. Early interpretation techniques (using straight-lines or log-log pressure plots) were limited to the estimation of well performance. With the introduction of the pressure derivative analysis[2] in the early "80s", and the development of modern interpretation techniques that are able to account for detailed geological features, PTA has become a very powerful tool in reservoir characterization.

In contrast, until recently, PDA has been mainly limited to decline curve analysis, which has been and remains an essential tool for reserve estimation suitable for investment purposes. PDA techniques have improved significantly over the past several years, and modern techniques are used to provide information on reservoir permeability, fracture length and conductivity, original hydrocarbon (oil and/or gas) in place, estimated ultimate recovery, well drainage area and skin amongst many.

Several items differentiate the processing of pressure transient analysis from production data analysis.

- For PTA, the selected period to be analyzed is usually a period where the noise in the response is low. This is generally a shut-in period. Conversely, PDA focuses on flow (production or injection) periods, and shut-ins are formally excluded.
- As a consequence, pressure build-up data frequently offer response patterns that can be diagnosed as flow regimes sensitive to various well and reservoir parameters, while PDA must contend with considerable redundancy and noise associated with frequent rate changes over time.

- For pressure transient analysis, the selected testing period is relatively short (hours, days, weeks) rather than months and years, which is the typical time frame of production data analysis.
- The PTA process usually consists in matching the pressure, using rates as an input. In PDA, the matched data are generally rates, or cumulative production, or productivity index.

1.1 Problem Description

In practice today, PTA and PDA are done separately and differently by different interpreters in different companies using different analysis techniques, different interpreter-dependent inputs, on pressure and production rate data from the same well, with different software packages. This has led to different analyses outputs and characterizations of the same reservoir. To avoid inconsistent results from different interpretations, the objective of this study is to combine both analyses on the same plot thereby enabling a unified interpretation for the entire producing life of the well.

1.2 Objectives

This study presents a new way to integrate PTA and PDA on a single diagnostic plot. The main purpose of this procedure is to be able to account for and see the early time and mid-time responses (from the transient tests) and late time (boundary affected/PSS) responses achievable with production analysis, on the same plot; thereby unifying short and long term analysis and improving the reservoir characterization

The primary objectives of this work are:

- To obtain a unique interpretation by combining PDA and PTA on a single diagnostic plot.
- To develop a simple, but robust method of processing data to improve the presentation of the analysis interpretation.
- To apply the techniques listed above to synthetic data and field well test and data obtained from wells in a vuggy naturally fractured reservoir (NFR) and in the Gulf of Mexico (GOM).
- To compare and validate this analysis technique with available techniques for both PTA and PDA in commercial software.

This study starts with a comprehensive literature review on the various diagnostic techniques available for PTA and PDA in practice today; describing their methods of application and listing the advantages and limitations of each technique.

Of the analysis methods already developed, the pressure change (Δp) and its derivative versus shut-in time; and the rate normalized pressure (RNP) and its derivative versus the material balance time - the methodology used in developing this new technique is then discussed. In this work, the RNP is preferred over the popular RNP integral function due to the errors in diagnosis (especially the event shifts in time) caused with the use of the RNP integral. Although the RNP integral was developed to reduce the noise in the interpretation of production data, the change in noise reduction is not that significant as compared to the RNP, and the potential for misdiagnosis from the use of the RNP integral does not justify its use. This has led to the development of new techniques to reduce data artifacts in the RNP to make it more usable.

1.3 Scope of Work

Generally well tests contain a series of different flow rates or a continuously varying flow rate, and the measured pressure responses are combinations of the pressure transients due to the varying flow rate. In this study, the rate normalized pressure (RNP) theory is applied and used to account for and normalize the pressure transients for varying rates. Conventional pressure transient analysis is applied to pressure build ups and both analyses (PDA and PTA) are plotted on a single diagnostic plot with resulting characteristic trends conserved and interpreted as for a continuous pressure drawdown response for flow at a constant rate.

The analysis is carried out with spreadsheets and VBA programming and the results are compared with the individual PTA and PDA results from commercial software. The field data examples represent two very different data processing and interpretation challenges. The carbonate reservoir combines a pressure build-up with long-term surface pressure and rate data acquired over several years. The Gulf of Mexico well has continuous pressure and rate data acquired every second for several months and fails to show evidence of closed reservoir limits.

CHAPTER II

LITERATURE REVIEW

2.1 Production Data Analysis as a Complement to Pressure Transient Analysis

Pressure transient tests are a means to evaluate well performance. They can determine whether poor producing quality was a result of well damage, poor formation permeability or low formation pressure. Because the pressure response is highly sensitive to changes in the well flow rate, pressure transient testing is usually conducted by shutting off production from the well. Pressure is recorded with a gauge that is usually located in the well near the productive interval. When the well is shut in, the wellbore pressure builds up, providing the pressure build-up response. Pressure build up tests exhibit characteristic responses that are readily recognized on the log-log plot of the pressure change and its derivative originally introduced by Bourdet, et al[2].

For a while, the pressure build-up response mimics the drawdown behavior that would be observed if the well could be flowed at a constant rate. In late time, the build-up response may be distorted due to superposition.

If wells were flowed for long periods at constant rate, the transient record would enable quantification of both near well and distant reservoir features. Instead, most wells are flowed at varying rates for many reasons. One reason is that many wells produce to a separator designed to operate at a particular pressure. Thus, constant pressure production may be more common than constant rate production. Another reason is that well rates are adjusted for operational reasons related to reservoir management involving multiple wells.

Because much has been written about PTA, this chapter is focused on PDA methods and why some methods could serve as a compliment to PTA.

2.2 Review of Production Data Analysis Methods

Production data analysis (PDA) started with empirical relationships. Today, PDA is evolving in a more analytical direction that offers well and reservoir characterization similar or complimentary to PTA. There are a number of commonly used methods for analyzing production data, including conventional and advanced decline curve analysis, automatic history matching and numerical reservoir simulation. Compared to PTA, there exists a dearth of literature about production data analysis. Although conventional decline curve analysis is virtually the only approved mechanism for proving reserves, because conventional decline curves are strictly empirical they are not favored by those interested in reservoir characterization, have received little attention in the scholarly literature and are hardly addressed in textbooks. This section reviews common PDA approaches in use today.

2.2.1 Production History Plot

This is a Cartesian plot of the rate and pressure versus time. Although not strictly speaking a PDA technique this plot helps visualize changes in rate and pressures with time as well as assess uncorrelated behaviors. A common example of an uncorrelated behavior is when the rate changes with no corresponding change in the pressure or vice-versa. Figure 2.1 below is a sample production history plot showing missing rates between 50 to 80 hours and uncorrelated pressure-rate behavior between 120 to 150 hours with a missing rate increase before the build-up in this time range.

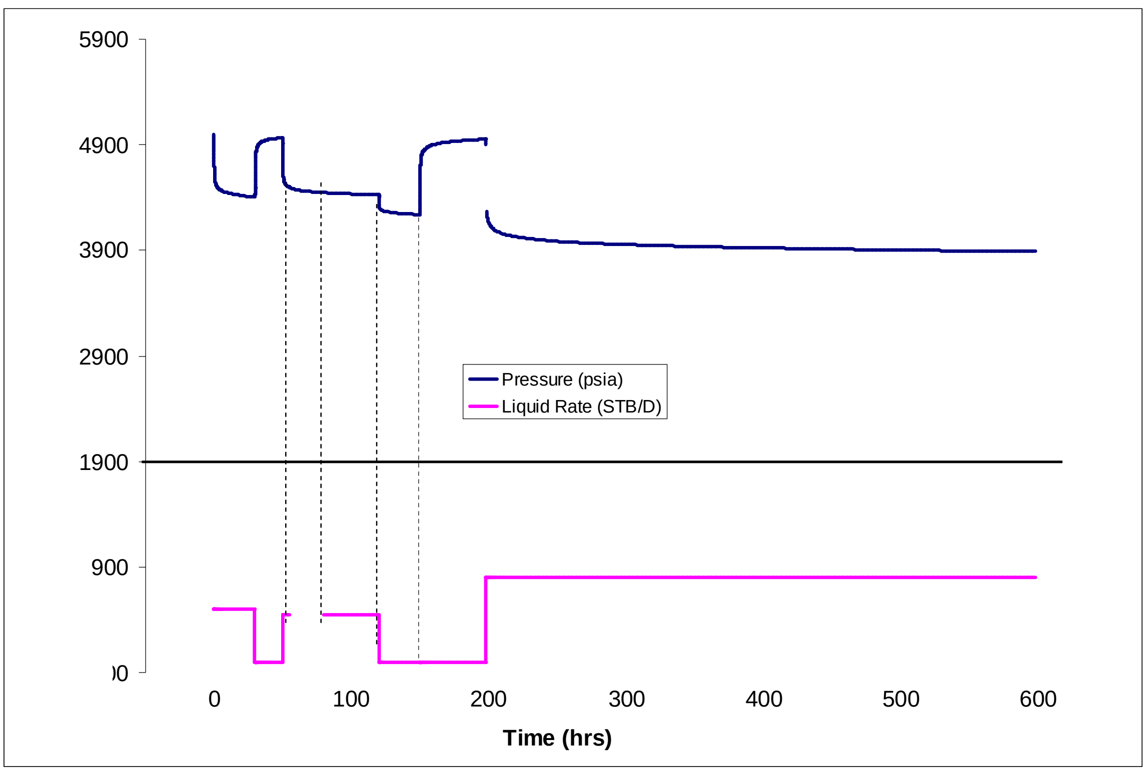

Figure 2.1: Production History Plot Showing Uncorrelated Pressure and Rate Data

2.2.2 Pressure-Rate Correlation

This is a simple plot of p_{wf} versus flow rate, used to assess the direct correlation of the rate and pressure data. This plot type (or variations of it) has had applications in the past, but Kabir and Izgec[3] formalized it as a diagnostic tool in 2006, as a means of identifying specific flow regimes. Figure 2.2 is an extract from the Kabir et al.[3] work that depicts a pressure-rate correlation plot intended as a practical diagnostic tool in a closed system for reservoirs with significant mobility producing gas or oil.

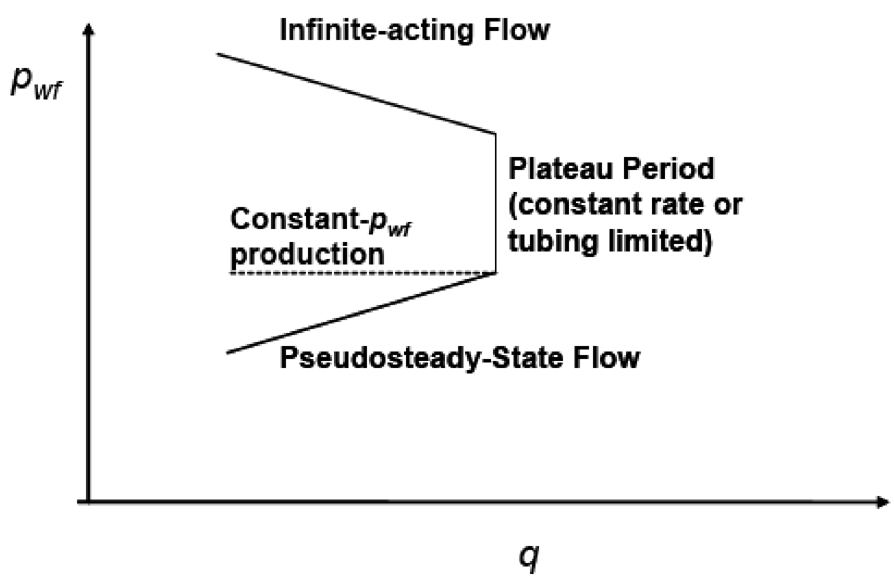

Figure 2.2: Plot of Wellbore Flowing Pressure Versus Well Flow Rate for a Closed System

As shown from the graph above, a negative slope implies infinite-acting radial flow period. The constant rate case yields a vertical line while a well produced at constant bottom hole flow pressure, p_{wf}, yields a horizontal line – zero slope. In contrast to the infinite acting flow regime, the pseudo-steady state flow regime gives a positive slope. Ilk et al.[4] showed some applications of this plot type in rationalizing uncorrelated rate and pressure data, noting transient rate spikes which occur with changes in rate.

2.2.3 Fetkovich Decline Type Curve

In 1980, Fetkovich[5] introduced a type-curve combining the theoretical response of a well in a closed reservoir, and the standard Arps decline curves to come up with a log-log matching technique applicable to both the transient and pseudosteady state flow periods. Fetkovich defined dimensionless variables (t_{Dd} and q_{Dd}) as:

$$q_{Dd} = \frac{q(t) \Big/ kh\left(p_i - p_{wf}\right)}{141.2\mu\beta\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]} = q_d\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right] \qquad \ldots\ldots\ldots\ldots \qquad 2.1$$

$$t_{Dd} = \frac{\dfrac{0.00634kt}{\phi\mu c_t r_w^2}}{\frac{1}{2}\left[\left(\frac{r_e}{r_w}\right)^2 - 1\right]\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]} = \frac{t_D}{\frac{1}{2}\left[\left(\frac{r_e}{r_w}\right)^2 - 1\right]\left[\ln\left(\frac{r_e}{r_w}\right) - \frac{1}{2}\right]} \qquad \ldots\ldots\ldots\ldots \qquad 2.2$$

Plotting q_{Dd} versus t_{Dd} yields the Fetkovich type curve plot as seen in Figure 2.3. Ehlig-Economides and Ramey[6] noted a minor discrepancy in these definitions stating that the ½ term should actually be ¾.

The primary use of this plot is for presenting data and model results as a log-log history plot. The main limitation of this plot is that it is valid only for the case of production at a constant bottom hole pressure[5].

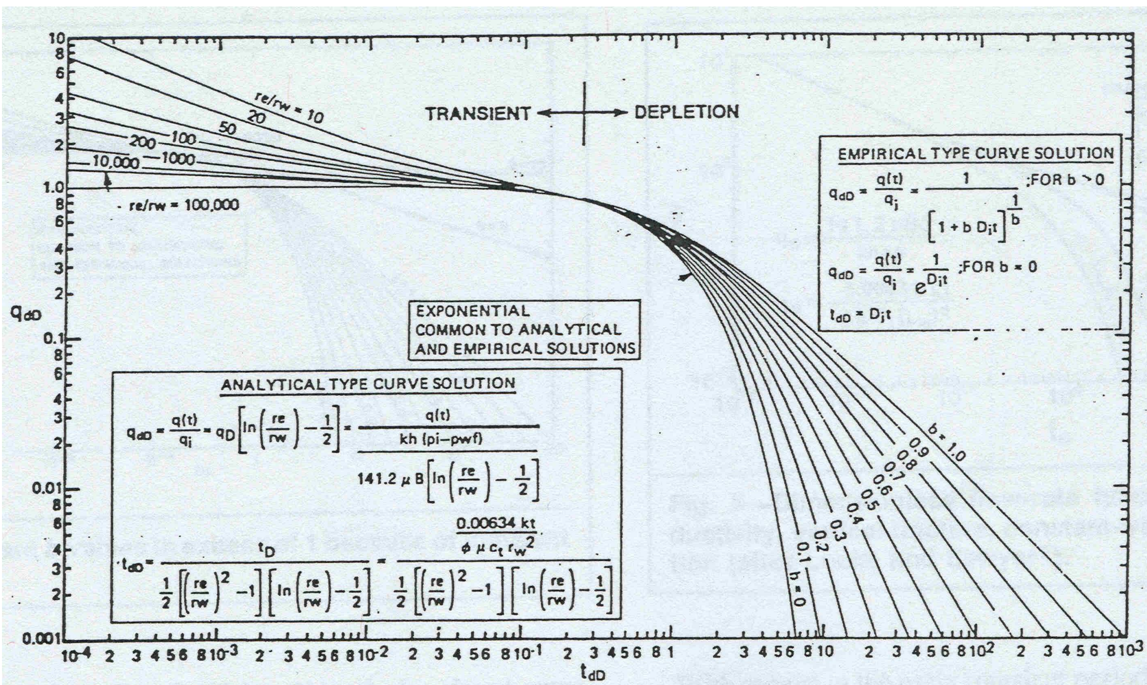

Figure 2.3: Fetkovich Type Curves (from Fetkovich et al. - 1987)

2.2.4 Rate Normalized Pressure (Reciprocal Productivity Index)

This is a log-log plot of the reciprocal of the productivity index versus the material balance time function. This diagnostic technique forms the basis of the new technique introduced by this work and as such will be discussed in more detail here.

This diagnostic technique was developed rigorously to account for variable rate flow in reservoirs. Starting with the material balance equation for a slightly compressible fluid which is given by Dake[7] as

$$\bar{p} = p_i - \frac{1}{Nc_t} N_p \qquad \text{........................} \quad 2.3$$

we consider the flow equation relating pressure drop and rate during the boundary-dominated (or pseudo-steady state) flow[7]. This expression is given as

$$\bar{p} = p_{wf} + qb_{pss} \qquad \text{........................} \quad 2.4$$

Combining equations 2.3 and 2.4 and solving for $\Delta p = p_i - p_{wf}$, we obtain

$$\Delta p = p_i - p_{wf} = \frac{1}{Nc_t} N_p + qb_{pss} \qquad \text{........................} \quad 2.5$$

Where the pseudosteady state constant, b_{pss}, is given by

$$b_{pss} = 141.2 \frac{\beta\mu}{kh}\left[\frac{1}{2}\ln\left(\frac{4}{e^{\gamma}}\frac{A}{C_A r_{wa}^2}\right)\right] \qquad \text{........................} \quad 2.6$$

The complete derivation of equation 2.5 from fundamental principles is detailed in the appendix of ref. 8.

Normalizing both sides of equation 2.5 by the flow rate, q, yields the rate normalized pressure (RNP)

$$\text{RNP} = \frac{(p_i - p_{wf})}{q_o} = \frac{\Delta p}{q} = \frac{1}{Nc_t} t_e + b_{pss} \qquad \text{........................} \quad 2.7$$

Where the material balance time,

$$t_e = \frac{N_p}{q} = \frac{Q_o}{q_o} \qquad \text{........................} \quad 2.8$$

From Equation 2.8, the material balance function is the cumulative production at any time divided by the instantaneous rate at that time.

The plot variables are shown in equations 2.7 and 2.8. Although typically noisy, this graph contains a response that mimics the long term drawdown behavior for the well in its drainage area.

2.2.4.1 RNP Derivative

Mimicking the approach used for PTA, the derivative of the RNP is simply computed as the derivative of the rate normalized pressure, $\Delta p/q$ with respect to the natural logarithm (ln) of the material balance time (t_e).

$$d(\mathrm{RNP}) \big/ d\ln(t_e) = \frac{[\mathrm{RNP}(t_{i+1}) - \mathrm{RNP}(t_{i-1})]}{[\ln(t_{ei+1}) - \ln(t_{ei-1})]} \qquad \text{.....................} \quad 2.9$$

2.2.4.2 RNP and Derivative Plot

This is a log-log plot of the RNP and its derivative (Equation 2.9) versus the material balance time. The resulting plot is an analog to the log-log plot of Δp and Δp derivative function versus time used in analyzing pressure drawdown under constant rate production[9]. The real value of the material balance time function is that it converts variable rate production to constant rate response behavior that can be matched with long-term drawdown models.

The log-log plot of $\Delta p/q$ versus material balance time can be used to diagnose flow regimes such as the infinite acting radial flow, linear or bi-linear flow, boundary dominated, etc. in wells. It depicts what part of the data set should be used to estimate a particular property (e.g., the infinite acting radial flow regime yields a constant derivative behavior from which permeability can be estimated). With this plot, boundary dominated flow will exhibit a unit slope line, similar to pseudosteady state flow in drawdown PTA. Furthermore, the derivative will exhibit a stabilization in the transient part at a level proportional to permeability.

Samples of these plots for simulated and field cases will also be shown, analyzed and discussed in detail in Chapter IV.

The main limitation of this technique is that the noise level is usually too high. Figure 2.4 is a sample graph of the RNP and its derivative against the material balance time showing a lot of noise and artifact in the presentation. Various techniques have been developed to help reduce this noise/unwanted data in the RNP presentation one of which is discussed next.

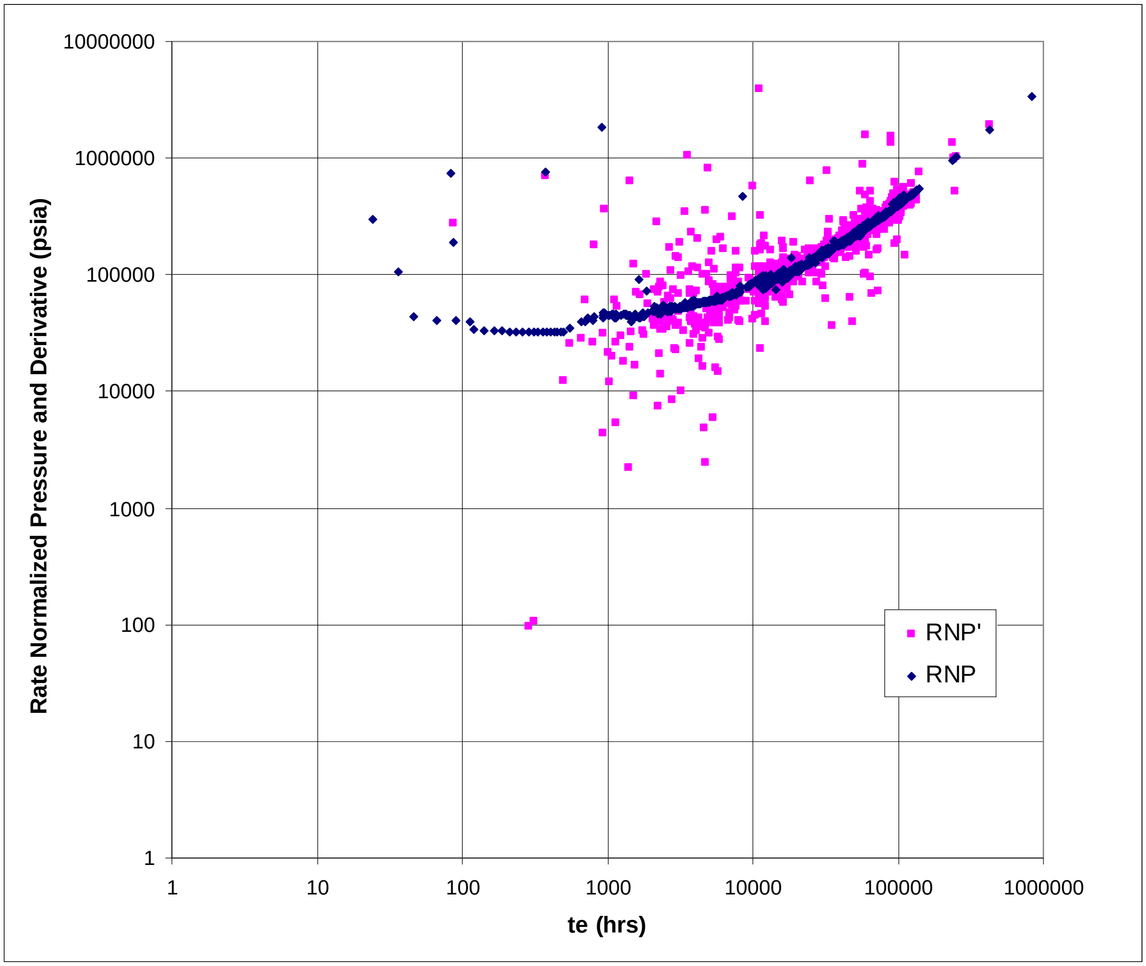

Figure 2.4: RNP Plot Showing Some Noise/Unwanted Data

2.2.5 Rate Normalized Pressure Integral

The RNP integral was developed to help reduce the noise in the log-log RNP versus t_e plot. The Palacio-Blasingame type curves[10] of the normalized RNP integral are currently referred to as the RNP. The integral of the RNP is calculated as in equation 2.10 and its derivative is calculated the same way as in equation 2.9 for the RNP derivative.

$$\text{RNP Integral} = \frac{1}{t_e}\int_0^{t_e} \frac{p_i - p_{wf}(\tau)}{q_o} d\tau \qquad \text{…………..} \qquad 2.10$$

Although this technique was developed to help reduce noise, which it does to an extent, its main drawback is that it causes a shift (in time) of events such as the start of the infinite-acting radial flow period or departures related to well drainage or reservoir boundaries. This leads to errors in quick look estimation of reservoir parameters, and can smooth away critical features in the transient response.

2.2.6 Advanced Decline Type Curve or Blasingame Plot

This is a re-plot of the traditional Fetkovich plot[5]. The limitation of the Fetkovich plot was the assumption of constant flowing pressure. Blasingame and McCray[11] noted that using a pressure normalized flow rate when the flowing pressure varies significantly didn't solve the problem, so they introduced two specific time functions, t_{cr} the constant rate time analogy , and t_{cp} for constant pressure. Palacio and Blasingame[10] introduced type curves that could be used for gases and Doublet et al.[12] applied this theory to oil production.

This plot is created by plotting the logarithm of productivity index ($q/\Delta p$) versus the logarithm of the material balance time function (Equation 2.8). This plot uses the rate normalized by pressure drop, instead of the pressure normalized by rate; and in some way is a corrected Fetkovich plot, that enables analysis of production data that has neither constant rate nor constant pressure[4].

When the normalized rate $q(t)/(p_i-p_{wf}(t))$ is plotted versus the material balance time function on a log-log scale, the boundary dominated flow regime follows a negative unit slope[1]. Figure 2.5 illustrates a Blasingame plot of a drawdown-buildup sequence of a simulated well case. The productivity index (PI), the PI integral and its derivative is plotted versus time as illustrated.

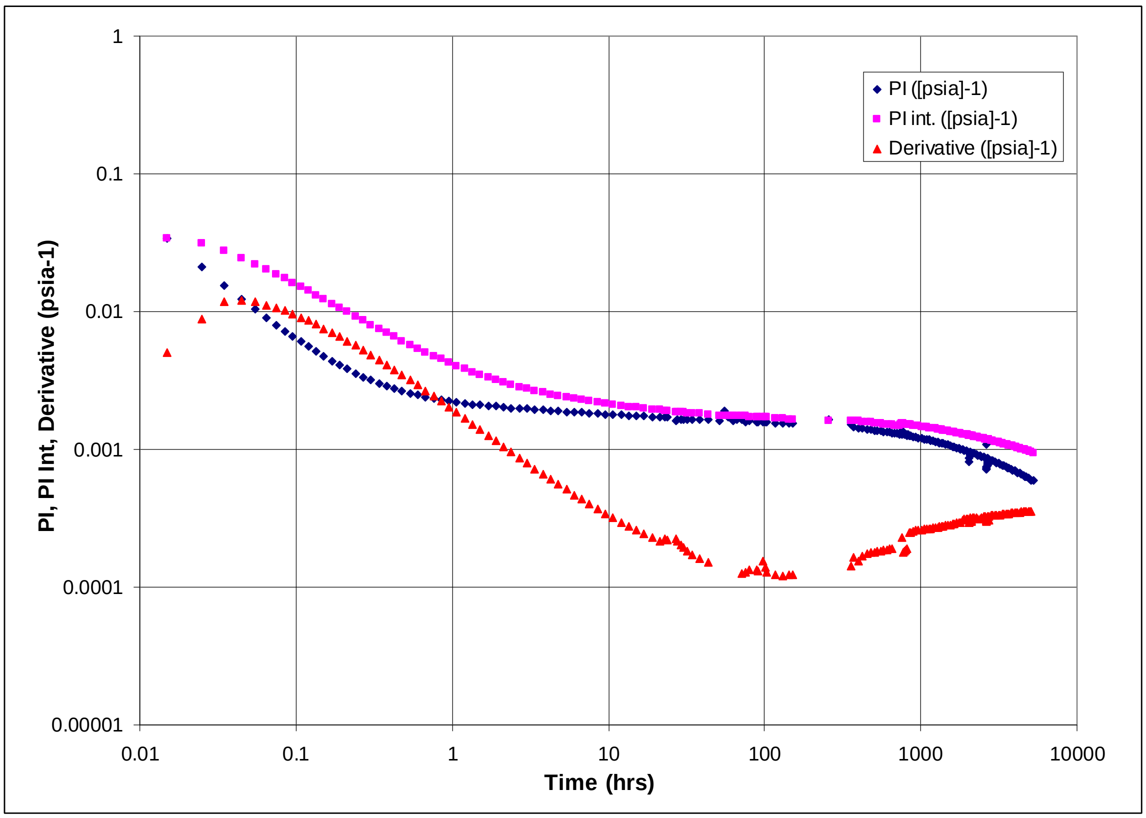

Figure 2.5: Blasingame Plot

Other references have been developed for the application of the work cited for the advanced decline type curve. Notable works include; Amini, et al.[13] for the elliptical flow case, Ilk, et al.[14] with the B integral derivative, Pratikno, et al.[15] for the finite conductivity fracture case and Marhaendrajana and Blasingame[16] for the multiwell case. These methods all require analysts to learn to diagnose completely different trends, and they do not reveal the simple trends we can see in a drawdown analog. This has led to the use of the RNP plot described earlier, as the basis in developing the new method described in the next chapter.

The move to modern production data analysis and corresponding commercial software is recent and came about mainly because (1) of performing classic decline analysis on a computer, and (2) permanent surface and downhole pressure gauges make real analysis using both rate and pressure data. Mattar and Anderson[17] and Anderson and Mattar[18] provide guidelines and examples for the diagnosis of production data with regard to model-based analyses (type curves). Several commercial production analysis packages, including the Topaze PDA module (Figure 2.6) of the KAPPA Ecrin package, have been released in the last few years.

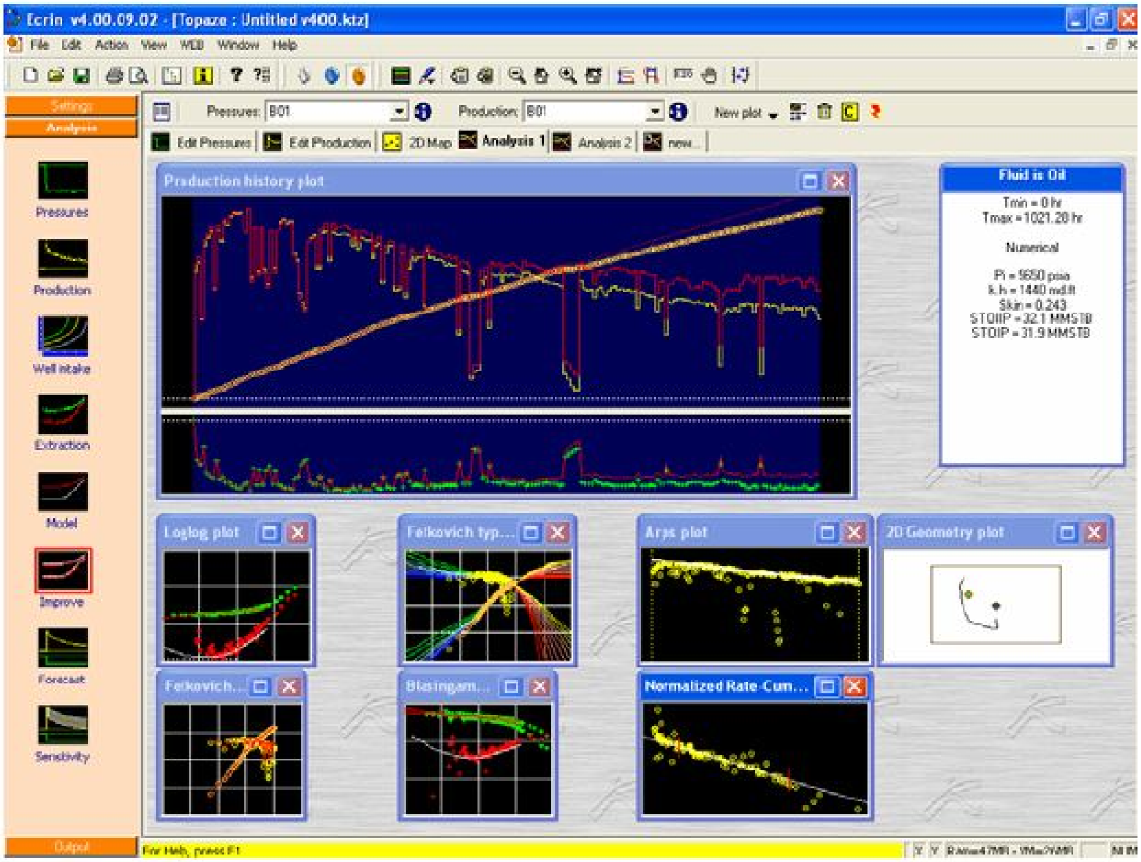

Figure 2.6: Modern Computer-Based PDA Software Package (Ecrin by KAPPA Engineering)

CHAPTER III

COMBINING PTA AND PDA

This chapter describes a new diagnostic method for long-term production data analysis. By long-term, we imply a means to view the entire production history of the well to show early-, mid- and late time characteristics enabled by combining PTA and PDA on a single diagnostic plot. In particular, the idea is to combine a selected pressure build-up with RNP representing the entire well production history. If the duration of the selected build-up is longer than the production data rate, the result is a continuous virtual drawdown.

Pressure transient tests are commonly run for relatively short periods - usually a few hours, with high quantities and quality of pressure data collected at a constant zero rate – while the well is shut in. These tests frequently reveal only well and near wellbore characteristics. On the other hand, typical production data are collected at the well usually at a daily (24 hour) rate (averaged daily) or monthly (averaged monthly) almost through the entire life of the well, giving an abundance of data that is sensitive to more distant reservoir heterogeneities and to reservoir or well drainage boundaries.

The plot variables will be the RNP and Δp and their derivatives versus shut-in (Δt) – and the material balance (t_e) times. Illustrations of this plot for both synthetic and real field data will be shown in Chapter IV.

3.1 Issues with the Material Balance Time t_e

As previously discussed, the material balance time is a time function that ensures that the RNP response appears as a single pressure drawdown transient for production at a constant rate. However, with large or significant changes in flow rate, the use of the t_e brings about issues in the interpretation. These issues are summarized in the set of tables in Table 3.1. The value of the cumulative production, Q_o is calculated as in equation 3.1 and the material balance time is calculated as in equation 2.8.

$$Q_o = \sum_{j=1}^{N} \frac{q_j}{24}\left(t_j - t_{j-1}\right) \qquad \text{............} \qquad 3.1$$

Table 3.1 – Issues with the Material Balance Time

Table 3.1a - Uniform production, dt = te

Time	qo	Qo	te
0	100	0.00	0.00
24	100	100.00	24.00
48	100	200.00	48.00
72	100	300.00	72.00
96	100	400.00	96.00
120	100	500.00	120.00
144	100	600.00	144.00
168	100	700.00	168.00
192	100	800.00	192.00
216	100	900.00	216.00
240	100	1000.00	240.00
264	100	1100.00	264.00
288	100	1200.00	288.00
312	100	1300.00	312.00
336	100	1400.00	336.00
360	100	1500.00	360.00
384	100	1600.00	384.00
408	100	1700.00	408.00

Table 3.1 - Continued

Table 3.1b - Slight changes in rate works fine for te

Time	qo	Qo	te
0	100	0.00	0.00
24	103	103.00	24.00
48	102	205.00	48.24
72	106	311.00	70.42
96	110	421.00	91.85
120	109	530.00	116.70
144	115	645.00	134.61
168	111	756.00	163.46
192	112	868.00	186.00
216	102	970.00	228.24
240	108	1078.00	239.56
264	119	1197.00	241.41
288	123	1320.00	257.56
312	124	1444.00	279.48
336	118	1562.00	317.69
360	113	1675.00	355.75
384	120	1795.00	359.00
408	128	1923.00	360.56

Table 3.1c - Increasing qo yields lower te

Time	qo	Qo	te
0	100	0.00	0.00
24	100	100.00	24.00
48	100	200.00	48.00
72	100	300.00	72.00
96	250	550.00	52.80
120	250	800.00	76.80
144	250	1050.00	100.80
168	250	1300.00	124.80
192	250	1550.00	148.80
216	250	1800.00	172.80
240	500	2300.00	110.40
264	500	2800.00	134.40
288	500	3300.00	158.40
312	500	3800.00	182.40
336	500	4300.00	206.40
360	1000	5300.00	127.20
384	1000	6300.00	151.20
408	1000	7300.00	175.20

Table 3.1 - Continued

Table 3.1d - Lowering qo yields ascending increase in te

Time	qo	Qo	te
0	1000	0.00	0.00
24	1000	1000.00	24.00
48	1000	2000.00	48.00
72	800	2800.00	84.00
96	800	3600.00	108.00
120	800	4400.00	132.00
144	800	5200.00	156.00
168	700	5900.00	202.29
192	700	6600.00	226.29
216	700	7300.00	250.29
240	700	8000.00	274.29
264	400	8400.00	504.00
288	400	8800.00	528.00
312	400	9200.00	552.00
336	400	9600.00	576.00
360	100	9700.00	2328.00
384	100	9800.00	2352.00
408	100	9900.00	2376.00

Table 3.1e - Build-Ups don't yield te

Time	qo	Qo	te
0	100	0.00	0.00
24	100	100.00	24.00
48	100	200.00	48.00
72	100	300.00	72.00
96	0	300.00	#DIV/0!
120	0	300.00	#DIV/0!
144	0	300.00	#DIV/0!
168	0	300.00	#DIV/0!
192	0	300.00	#DIV/0!
216	0	300.00	#DIV/0!
240	0	300.00	#DIV/0!
264	0	300.00	#DIV/0!
288	100	400.00	96.00
312	100	500.00	120.00
336	100	600.00	144.00
360	100	700.00	168.00
384	100	800.00	192
408	100	900.00	216

Table 3.1 - Continued

Table 3.1f - For two BUs, te < total time

Time	qo	Qo	te
0	100	0.00	0.00
24	100	100.00	24.00
48	100	200.00	48.00
72	100	300.00	72.00
96	100	400.00	96.00
120	0	400.00	#DIV/0!
144	100	500.00	120.00
168	100	600.00	144.00
192	100	700.00	168.00
216	100	800.00	192.00
240	0	800.00	#DIV/0!
264	100	900.00	216.00
288	100	1000.00	240.00
312	100	1100.00	264.00
336	100	1200.00	288.00
360	100	1300.00	312.00
384	100	1400.00	336.00
408	100	1500.00	360.00

Table 3.1g - Very small values in qo yield very large te

Time	qo	Qo	te
0	100	0.00	0.00
24	105	105.00	24.00
48	111	216.00	46.70
72	109	325.00	71.56
96	116	441.00	91.24
120	102	543.00	127.76
144	109	652.00	143.56
168	119	771.00	155.50
192	121	892.00	176.93
216	86	978.00	272.93
240	20	998.00	1197.60
264	2.333	1000.33	10290.61
288	0.6	1000.93	40037.32
312	0.0004	1000.93	60056004
336	50	1050.93	504.45
360	86	1136.93	317.28
384	100	1236.93	296.86
408	102	1338.93	315.04

Table 3.1 - Continued

Table 3.1h - Unusually high qo causes distortions in te

Time	qo	Qo	te
0	100	0.00	0.00
24	100	100.00	24.00
48	100	200.00	48.00
72	100	300.00	72.00
96	100	400.00	96.00
120	6000	6400.00	25.60
144	100	6500.00	1560.00
168	100	6600.00	1584.00
192	100	6700.00	1608.00
216	562322	569022.00	24.29
240	100	569122.00	136589.28
264	20000	589122.00	706.95
288	100	589222.00	141413.28
312	100	589322.00	141437.28
336	100	589422.00	141461.28
360	100	589522.00	141485.28
384	100	589622.00	141509.28
408	100	589722.00	141533.28

Uniform production or constant rate results in the material balance time equaling the producing time (Table 3.1a). This is an ideal case and it is never encountered in actual field production.

Table 3.1b shows the material balance time monotonically increasing for slight changes in rate, thereby converting a variable rate case to an equivalent constant rate drawdown.

Monotonically increasing rate changes result in the material balance time being less than the actual producing time (Table 3.1c), and vice-versa for monotonically decreasing rates (Table 3.1d). Notably, build-ups don't yield t_e values and eventually result in t_e being less than the producing time (Tables 3.1e and 3.1f).

Very large rate changes cause erroneous values in t_e. This is evident in Tables 3.1g and 3.1h. Very small rate values result in very large values in t_e, and vice-versa. Large rate changes are common in field practices and are apparent in wells with installed permanent downhole gauges. These extraneous values result in outliers on the RNP plots that should be considered artifacts. In this study, special care is taken to identify these issues and exclude the data points from the presentation.

3.2 Issues with the RNP Integral

The RNP integral function has been introduced in Chapter II. It is expressed mathematically in equation 2.10 and was developed to reduce the noise in the RNP plot to aid presentation and interpretation.

$$RNPIntegral = \frac{1}{t_e}\int_0^{t_e} \frac{p_i - p_{wf}(\tau)}{q_o} d\tau \qquad \text{.............} \qquad 2.10$$

Although this reduced noise to some extent, it still does not take out most of the noise, and worse off, it causes time shifts in events and misses some features altogether. The interpretation errors that result from the use of the RNP integral overshadow the benefit of its use in cleaning up some of the noise. To illustrate some of these problems, production data analyses is carried out on a simulated well in a rectangular reservoir with dual porosity, two no flow boundaries (North and South) 2000 ft away from the well; and two constant pressure boundaries (East and West) 7000 ft away from the well. Figure 3.1 shows the production data analysis carried out on the well, comparing the RNP and the RNP integral with their respective derivatives. The valley-shaped feature beginning at the end of the wellbore storage is characteristic of dual porosity reservoirs and is evident on the RNP derivative at t_e between 1.2 hours and 8 hours and is absent in the RNP integral presentation. As well, the transient response due to boundary features is distorted, and the timing of the departure from infinite-acting flow (constant derivative) response is earlier in time for the RNP integral. For these reasons, this study uses the RNP and has investigated other ways to reduce the noise in the RNP response.

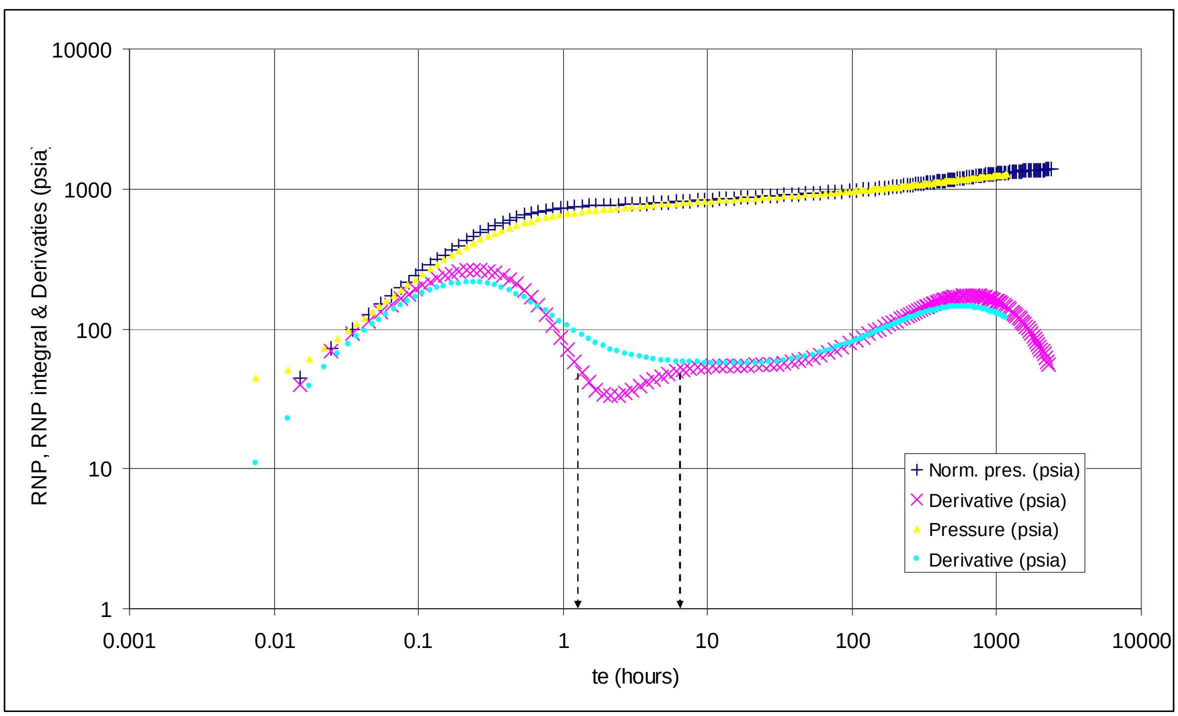

Figure 3.1: Comparing the RNP and the RNP Integral

3.3 Data Handling

As discussed previously, there are artifacts associated with the use of the RNP technique. Instead of noise, the term "artifact" is used here because these points have no diagnostic value in actual interpretation and reduce the quality of the plot presentation. One type of artifact results from the computation of the material balance time as displayed in Table 3.1. In this study, simple logical algorithms were formulated and applied to computed data to remove such artifacts.

With t_e computations and RNP plots, three major artifact types are evident:

- Upward and downward trends that are associated with transients caused with rate changes, especially following build-ups.
- Far outliers caused by the material balance times with very large changes in rate, and
- Analysis of too many data points that tend to cloud event signatures.

Noise in production data relates to the quality of rate and pressure measurements. Probably a big source of noise is related to the disparity in the locations for the pressure and rate gauges and that these measurements are acquired using different clocks and are often acquired at different data rates. Also, while each well may have a permanent downhole pressure gauge, production rate data frequently is not acquired for each well and represents a back allocation from the combined rates for several wells flowing into a common gathering system. Typically field data shows many instances of rate changes with no evidence in the pressure data and vice-versa.

Data processing algorithms for artifact removal also help to remove some of the noise in the data to yield a much more straightforward interpretation plot.

3.3.1 Upward and Downward Trends

Each rate change reproduces the same or nearly the same transient result in the pressure change response. For the RNP, pressure change is computed as the difference between the initial reservoir pressure and the time dependent measured transient pressures. If instead, for a given rate change, the pressure difference is between the pressure just before the rate change and the transient pressures measured after the rate change, a response very much like a typical pressure buildup response will result. In the RNP graph in Figure 3.2, the behavior shown in the graph inserts is collapsed in a short interval of the logarithm of the material balance time.

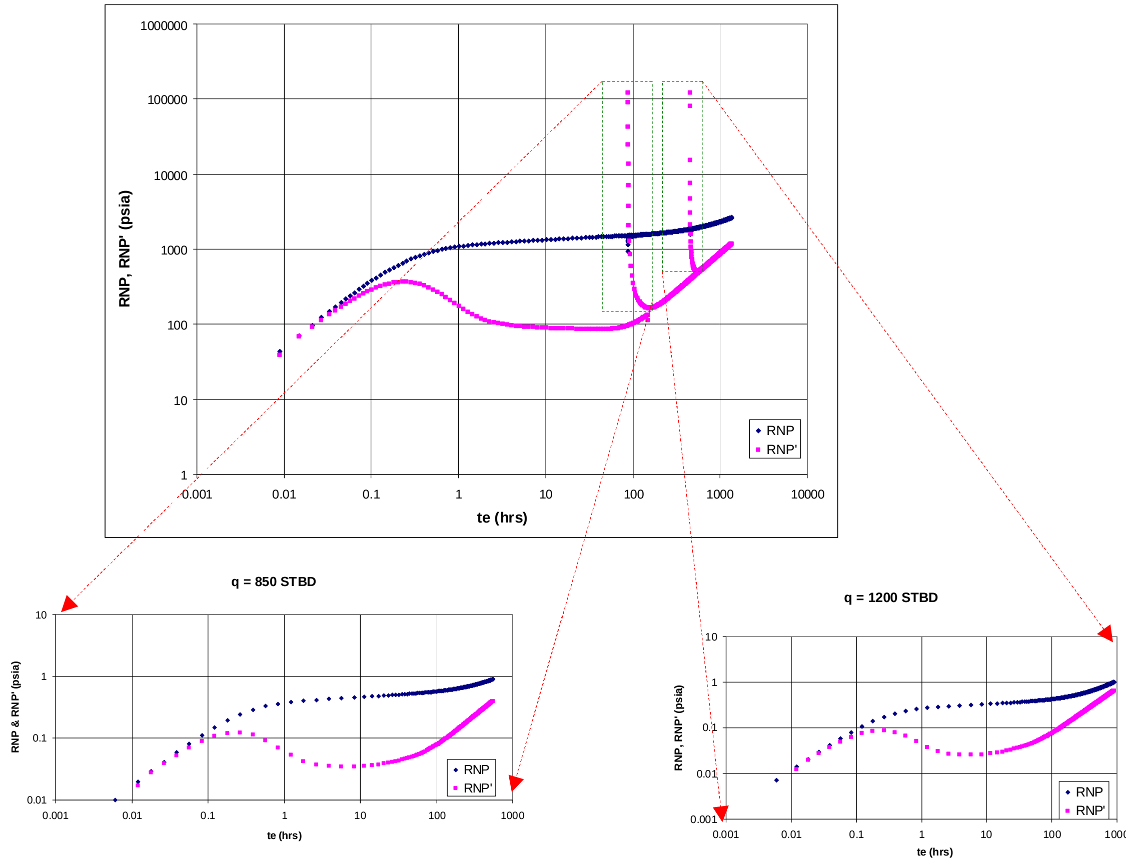

Figure 3.2: Cause of Upward and Downward RNP Artifacts

In early time a rate increase causes a (sometimes sharp) increase in the RNP and a (sometimes sharp) rate decrease causes a sharp decrease. The corresponding RNP derivative responses are discontinuities. The rate increase causes a jump to a very high RNP derivative that sharply drops like that in the left insert in Figure 3.2. The rate decrease causes a declining RNP and, therefore, a negative RNP derivative, as seen in the right insert in Figure 3.2. These short term responses are redundant reproductions of the early time response that should be removed from the RNP and derivative presentation.

These short term responses do not occur in typical production data acquired on a daily or monthly basis, but they do appear in production data acquired at higher data rates achievable with downhole permanent pressure gauges and subsea multiphase flow meters. These can be seen in synthetic data depending on what time values are computed.

For the upward and downward trends, the following excel command is applied to the RNP and RNP derivative columns after computation.

$$RNP_k = IF\left[AND\left(t_{e\,i} > \left(t_{ei-1} * c\right), RNP_i^{'} < RNP_i\right), RNP_i, ""\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad 3.2$$

$$RNP_k^{'} = IF\left[AND\left(-4 < m < 2, t_{e\,i} > \left(t_{ei-1} * m\right), RNP_i^{'} < RNP_i\right), RNP_i^{'}, ""\right] \quad \ldots\ldots\ldots\ldots \quad 3.3$$

$$m = \frac{Log\left(\dfrac{RNP_i^{'}}{RNP_{i-1}^{'}}\right)}{Log\left(\dfrac{t_{ei}}{t_{ei-1}}\right)} \quad \ldots\ldots\ldots\ldots\ldots \quad 3.4$$

where

RNP’ is the derivative of the RNP.

c is a constant used to regress and typically ranges between 1.002 to 1.007.

m is a slope function of the RNP derivative plot

Equation 3.2 instructs the spreadsheet to output values of RNP if its corresponding time, t_e is greater than the preceding t_e value by a factor of c. The interpreter regresses on the value of c until a "clean" trend in the RNP is obtained. Equation 3.3 applies the slope function m, to the data set along with the logic applied for the RNP. Most known reservoir signatures on the RNP derivative plot fall between the -3 and +1 slopes. The actual values used in the logic equation allows for some measure of noise in the data because use of this algorithm on real data proved to be too restrictive, thereby leaving too little response in the graph.

This logic has shown to clean up most of the up- and down turners, and noise in plotted RNP data. Figure 3.3 illustrates an example of a simulated well producing with variable rates, comparing the RNP and RNP' plots before and after the clean-up algorithms were applied.

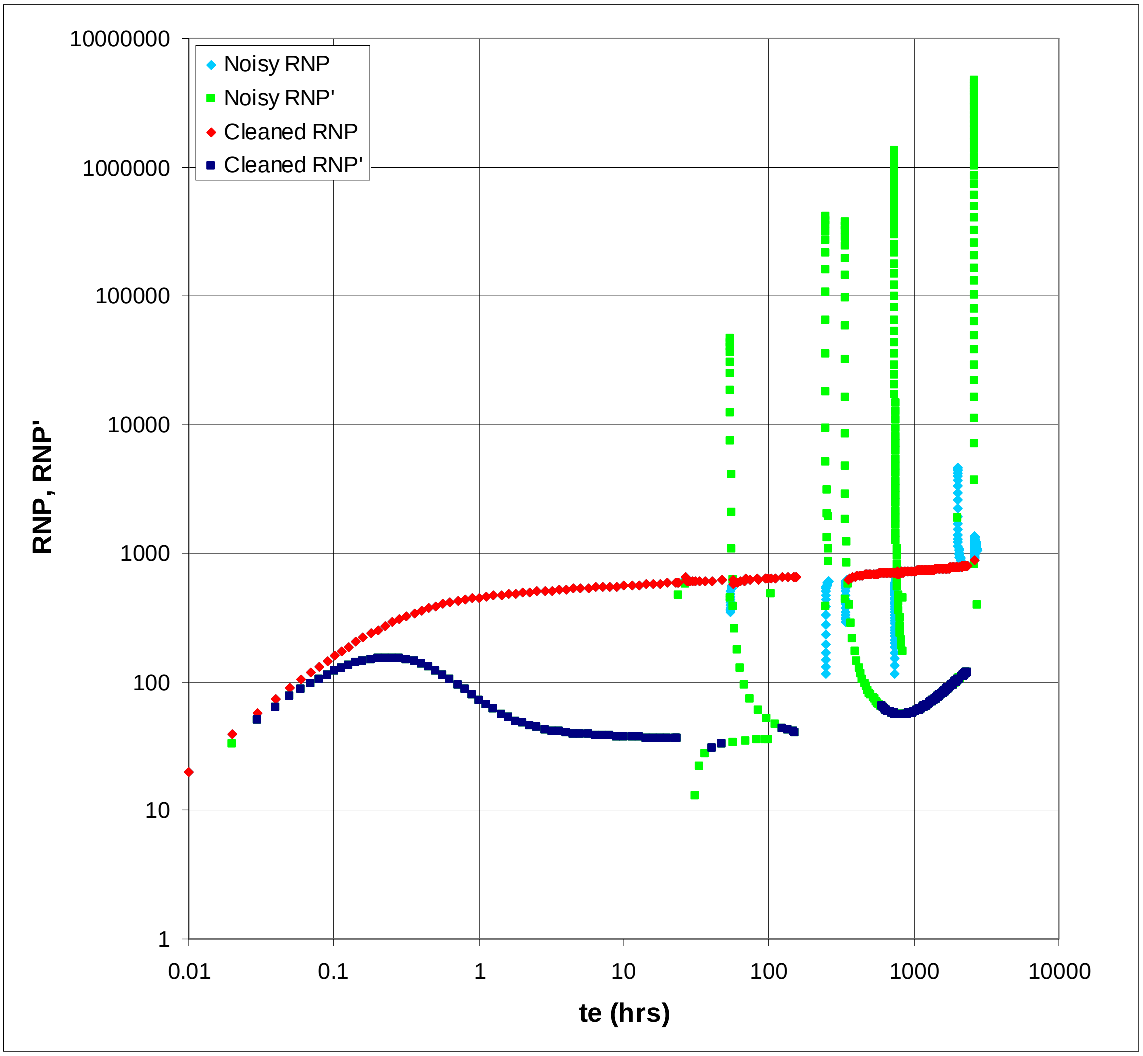

Figure 3.3: Logic Applied to Remove Upward and Downward RNP artifacts

3.3.2 Far Outliers

These are artifacts appearing when there is a large difference in rate, as displayed in Table 3.1g and 3.1h. These large rate differences are typical of field data. The easiest way to handle these artifacts is simply not plotting these points; or points that are greater than the actual producing time of the well. These points are simply artifact and should not be used in interpretation – as it would only imply interpreting "future time". Figure 3.4 illustrates this kind of error and the plot values truncated at the actual well producing time. No other noise technique had been applied here.

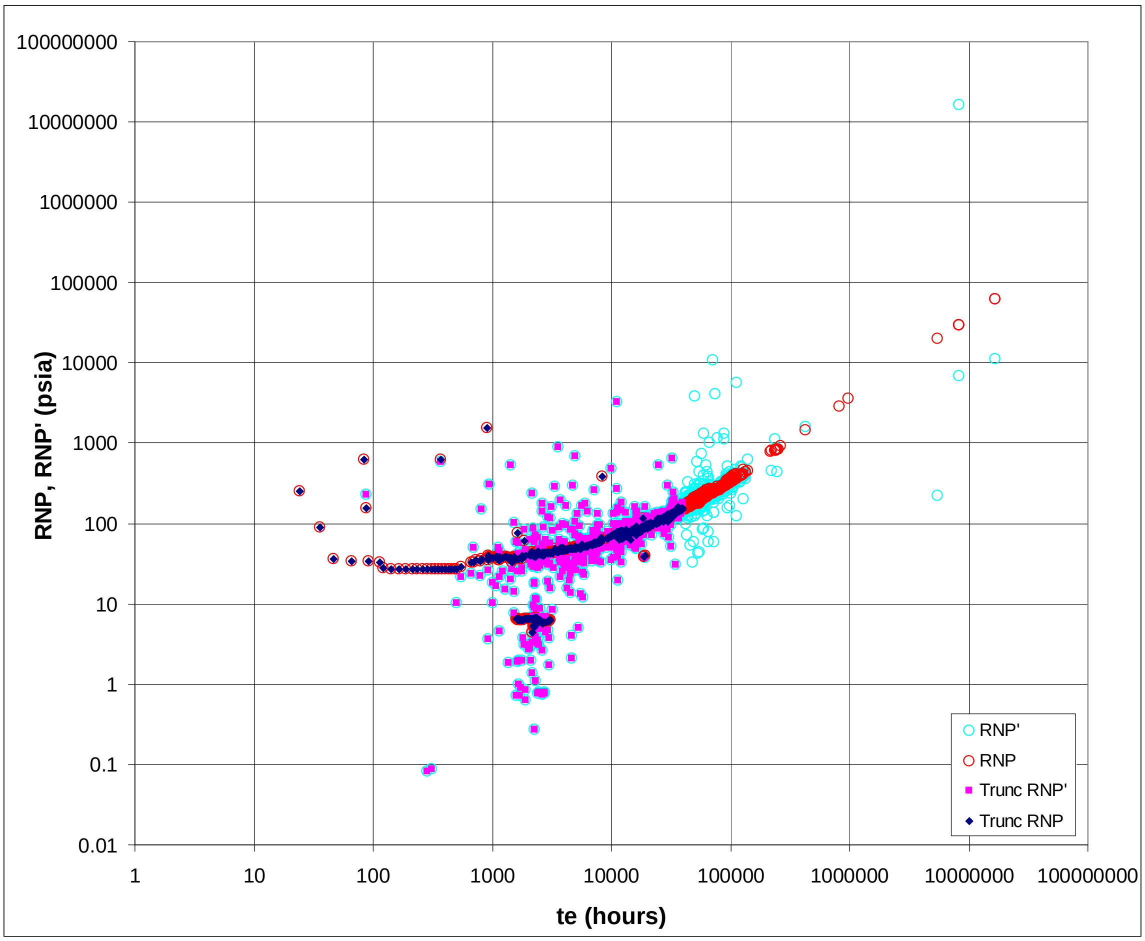

Figure 3.4: Truncating t_e at Total Producing Time

3.3.3 Too Many Points

With the advent of permanent downhole gauges (PDG) and continuous data collection, the "solution" to inadequate interpretation data has become a "problem" of too many data points. With the increasingly frequent installation and use of PDGs and other measuring instruments, we are receiving data at a high acquisition rate and over a long interval. Put crudely, if we multiply high frequency by long duration, we get a huge number (in millions) of data points, typically 20 – 300 million.

Conversely, the number of data points needed for an analysis is much less. For production data analysis, if rates are acquired daily, a pressure point per hour will do. This means less than 100,000 points for ten years. For pressure transient analysis, 1,000 points extracted on a logarithmic time scale is sufficient. Assuming 100 build-ups, coincidentally this is another 100,000 points[1].

In this study we have used a simple technique of picking equally spaced points on a logarithmic cycle. This is achieved using the equation 3.5 and creating an Excel Visual Basic for Application (VBA) algorithm to generate equally spaced numbers logarithmically starting from the minimum value for t_e; and to output actual t_e values closest to each of the reduced points to be used for interpretation.

$$t_j = t_{j-1} * 10^{\frac{1}{n}} \qquad \text{.................................} \quad 3.5$$

Where

t is the reduced time set, and

n is the number of points per logarithmic cycle

This helps clean the cloud caused by interpreting too many data points by reducing the plotted points whilst still conserving signatures. Figure 3.5 shows a sample build-up data set with too many data points collected from a permanent downhole gauge. Figure 3.6 shows this technique applied comparing plotted points of the reduced data set with the data set before the technique was applied. The apparent diagonal trends in the derivative response are probably caused by the aliasing effect in electronic data gauges[19]. To apply the logarithmic data reduction to the RNP and derivative data, the data are first re-ordered in material balance time.

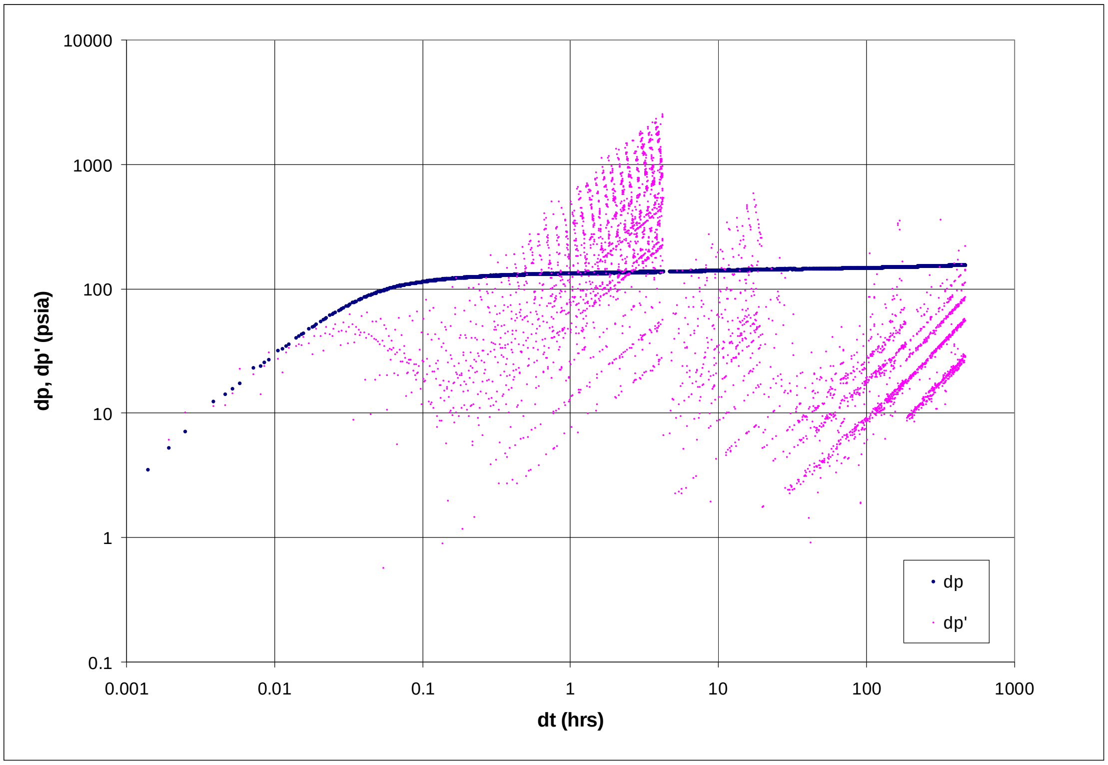

Figure 3.5: Sample Data Set with Too Many Points

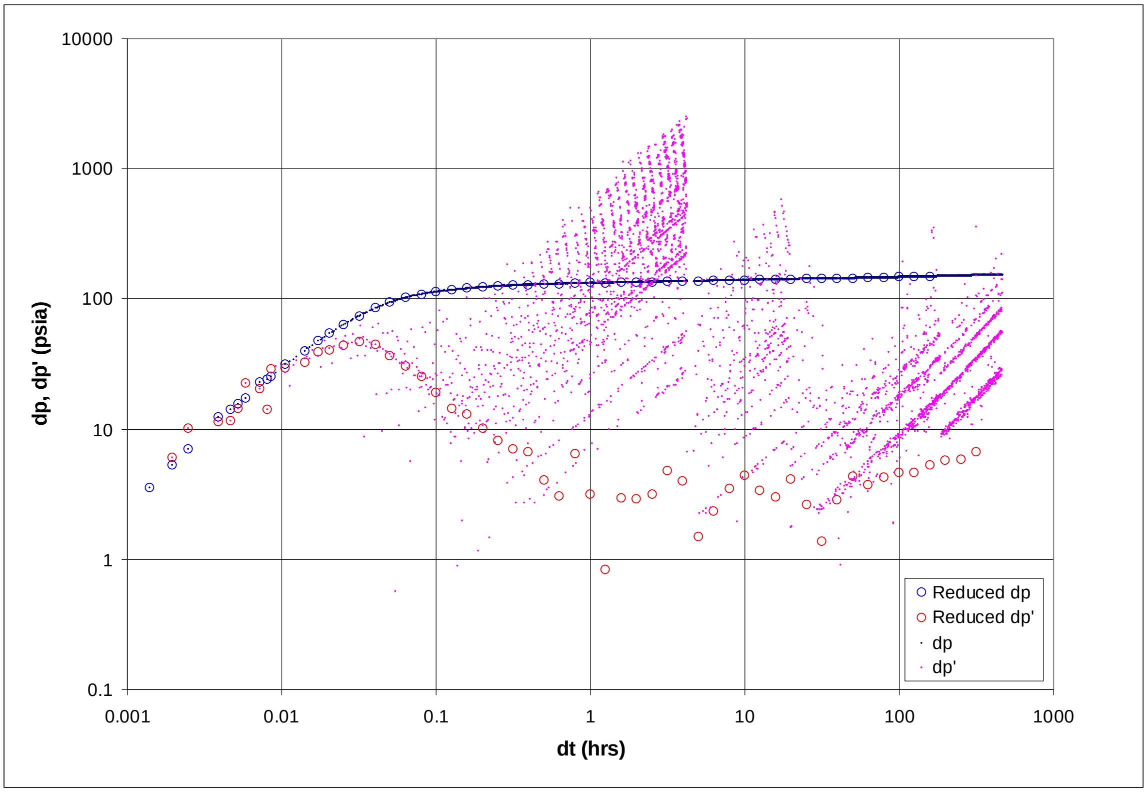

Figure 3.6: Logarithmic Data Reduction

CHAPTER IV

APPLICATION AND DISCUSSION

This chapter provides detailed information on how to use this combined PTA and PDA method. The theory of the technique has been discussed in Chapter III and the plot and plotting variables introduced. To apply this technique, we will list a stepwise analysis/interpretation procedure for production data and then illustrate the procedure with example data. The first example is a simulated well case designed using commercial well test software. Since the data in this example are simulated, they provide a better match than we would see in actual field examples. We feel that these examples allow the reader to become familiar with the calculation procedure in a clear and concise manner.

Next we will try two field examples; a well from a vuggy naturally fractured reservoir in China, and another from a Gulf of Mexico field.

4.1 Stepwise Analysis Procedure

In order to improve analysis, we employ the following step-by-step process for the diagnosis and analysis of the production data.

1. Assess Data Viability: - This is a preliminary data review to determine whether or not a production data set can (or cannot) be analyzed based on the

availability of historical rates and pressures, reservoir and fluid data (for quantitative analysis) and well records (completion or stimulation history).

2. Quality Check (QC) the Data: - This is the intermediate step between data acquisition and analysis. It entails creating rate-time and pressure-time plots otherwise known as the production history plot. These can show features or events which should be filtered or discarded such as poor early measurements.
3. PTA and PDA plots: - The individual plot variables, Δp, Δt, RNP, t_e and the derivatives are calculated for build-ups and the entire production history.
4. Clean/Edit Data for Clarity: - The data processing techniques are applied here to remove the artifacts from the log-log plots used for diagnosis.
5. Combine Plots: - Both PDA and PTA plot variables are plotted on a single log-log plot.
6. Identify flow regimes and match build-up and RNP response together.

Now that we have the basic analysis procedure, we can apply them to the examples.

4.2 Example 1: Simulated Well Case

Using the test design capabilities in the Ecrin-Saphir software, a well is placed in the center of a "square-shaped" bounded- dual porosity reservoir. The no-flow boundaries are located 8,000 feet from the wellbore.

This example uses the following reservoir and fluid data:

p_i = 5000 psia	ϕ = 0.1
h = 30 ft.	μ = 1.0 cp
β_o = 1.0 rb/STB	$c_t = 3.0 * 10^6$ psia^{-1}
r_w = 0.3 ft.	k = 333 md

The production schedule for this well is shown in Table 4.1, and pressures are generated for these rates. The production rate and pressure data are exported to a Microsoft Excel spreadsheet and plot variables are calculated manually using the equations in Chapter III.

Table 4.1 – Production Schedule for Example 1

Duration (hr)	**Liquid Rate (STB/D)**
24	500
76	450
100	850
100	0
100	50
10	550
100	70
30	0
100	200
5000	500

Firstly we review the data using the production history plot (Figure 4.1). In this case, it is seen that the data correlation is excellent since it is a simulated example. Data viability is not an issue as required well, fluid and reservoir parameters were input before the pressure data was simulated.

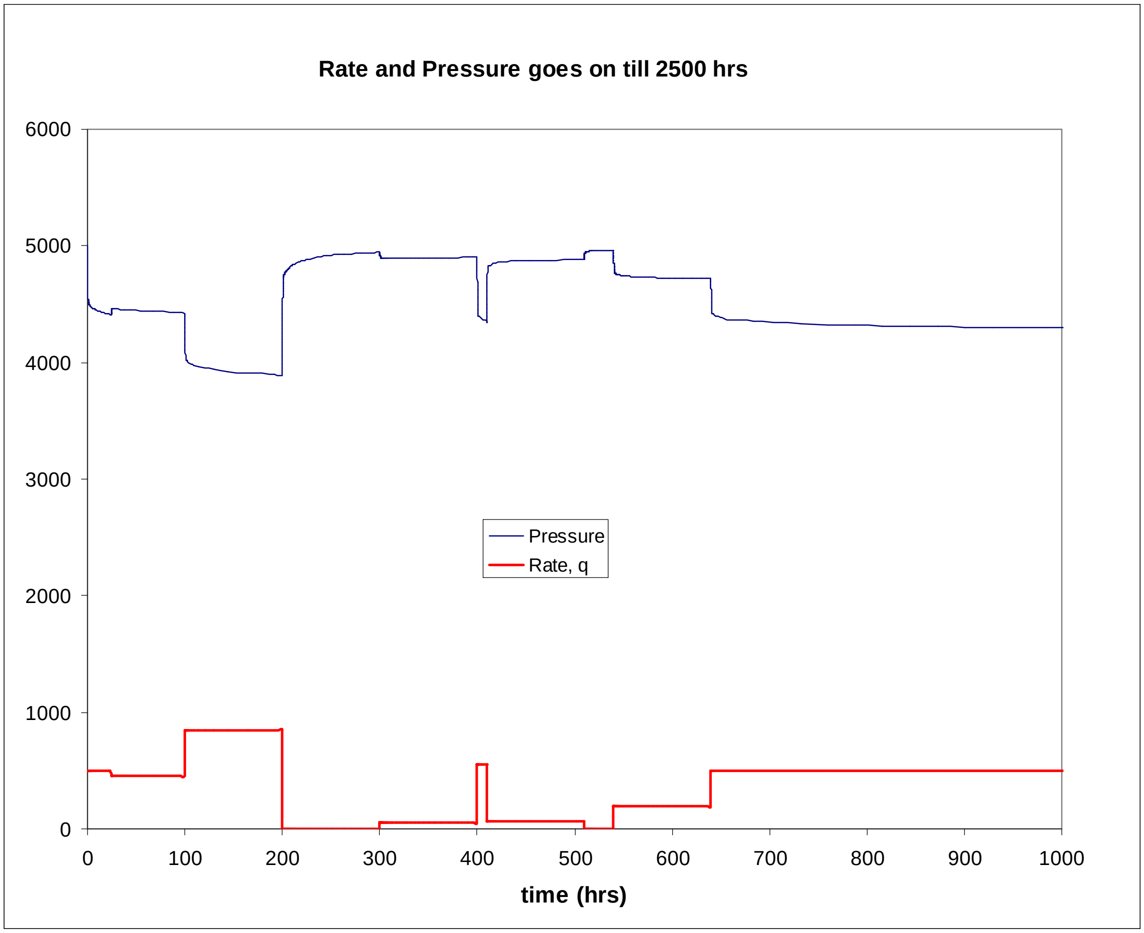

Figure 4.1: Production History Plot for Example 1

With simulated pressures and input rate information, the PDA plot variables (RNP, t_e and the derivative) were calculated and normalized to the last rate before the selected build-up (build-up 1). Build-up pressures were extracted and treated separately, calculating the Δp, Δt and the derivative (PTA plot variables). Figure 4.2 is the PTA plot of build-up 1 and Figure 4.3 is the PDA plot before the data artifacts were removed.

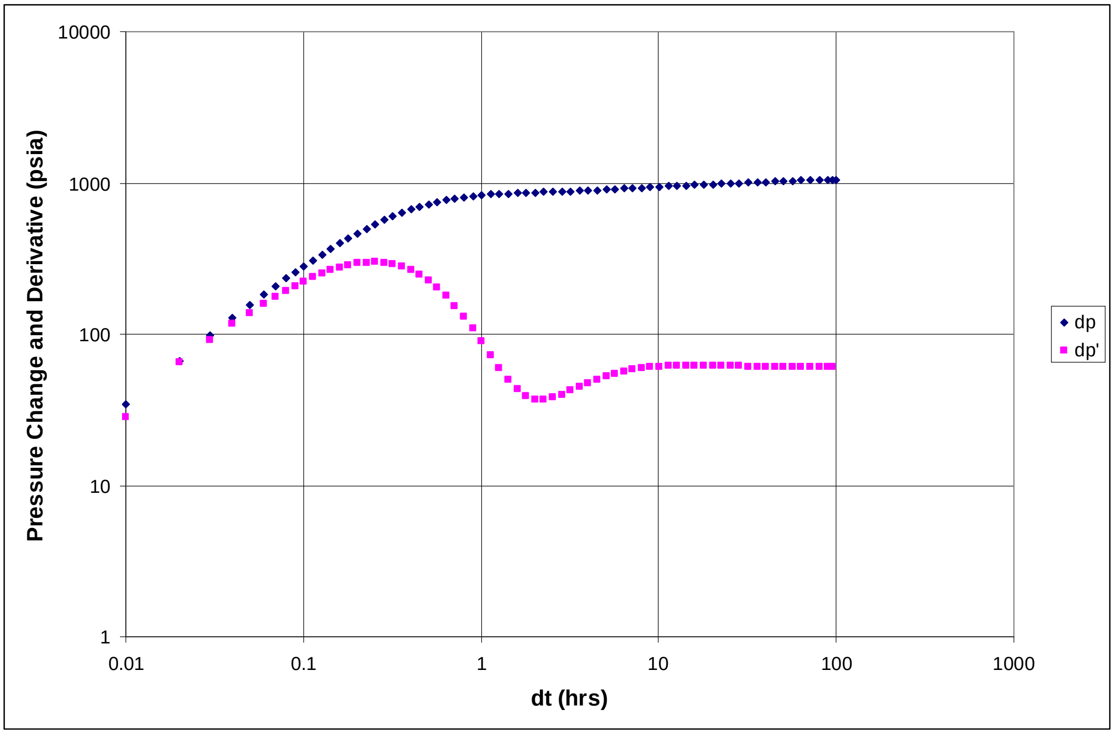

Figure 4.2: PTA Plots of Build-Up 1

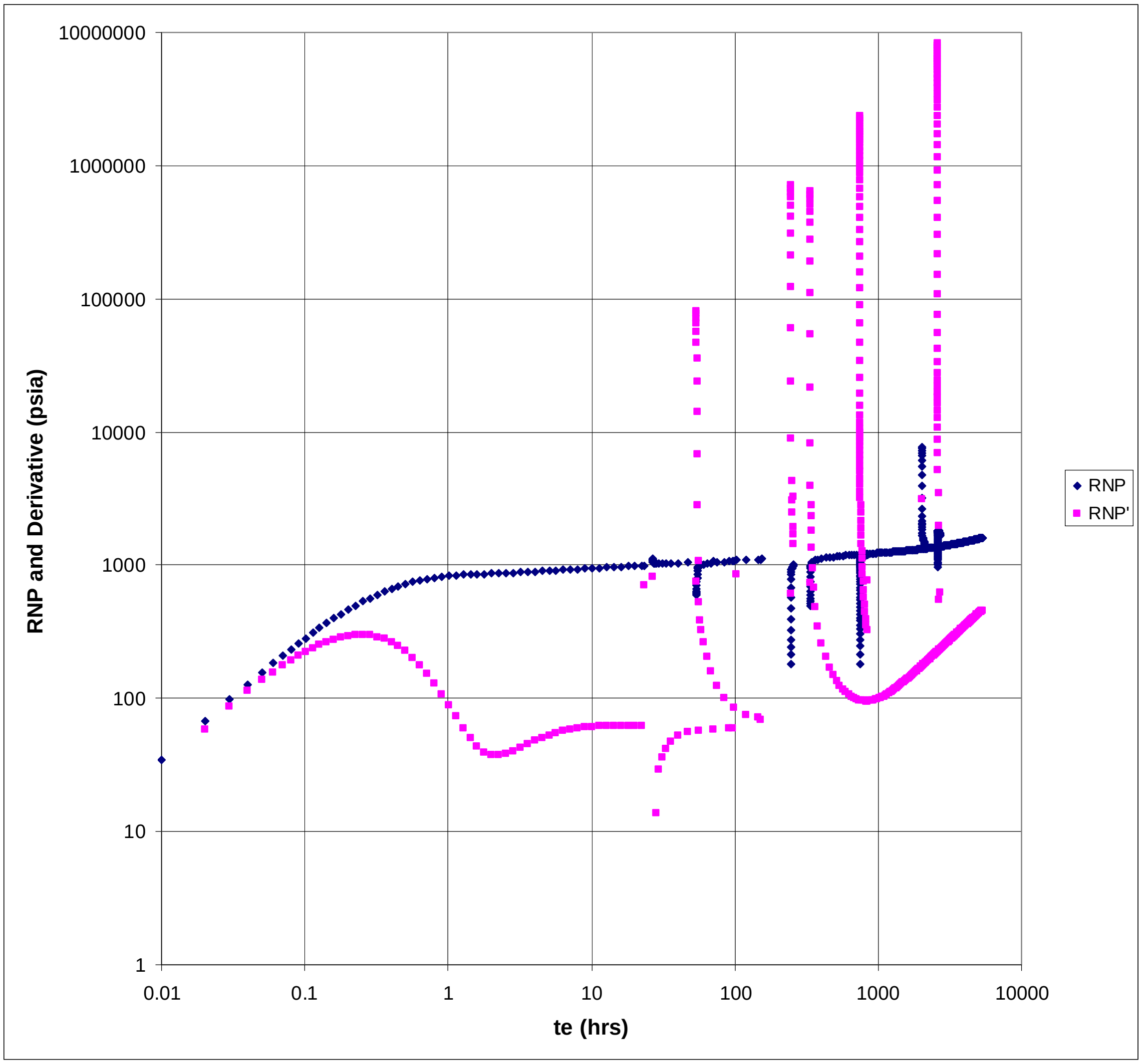

Figure 4.3: PDA Plot

Typical with the RNP plot of production data acquired at a high data rate, Figure 4.3 shows artifacts or unwanted data. When data is acquired daily for the drawdown sequence in Table 4.1, the RNP plot will have very little artifacts as shown in Figure 4.4.

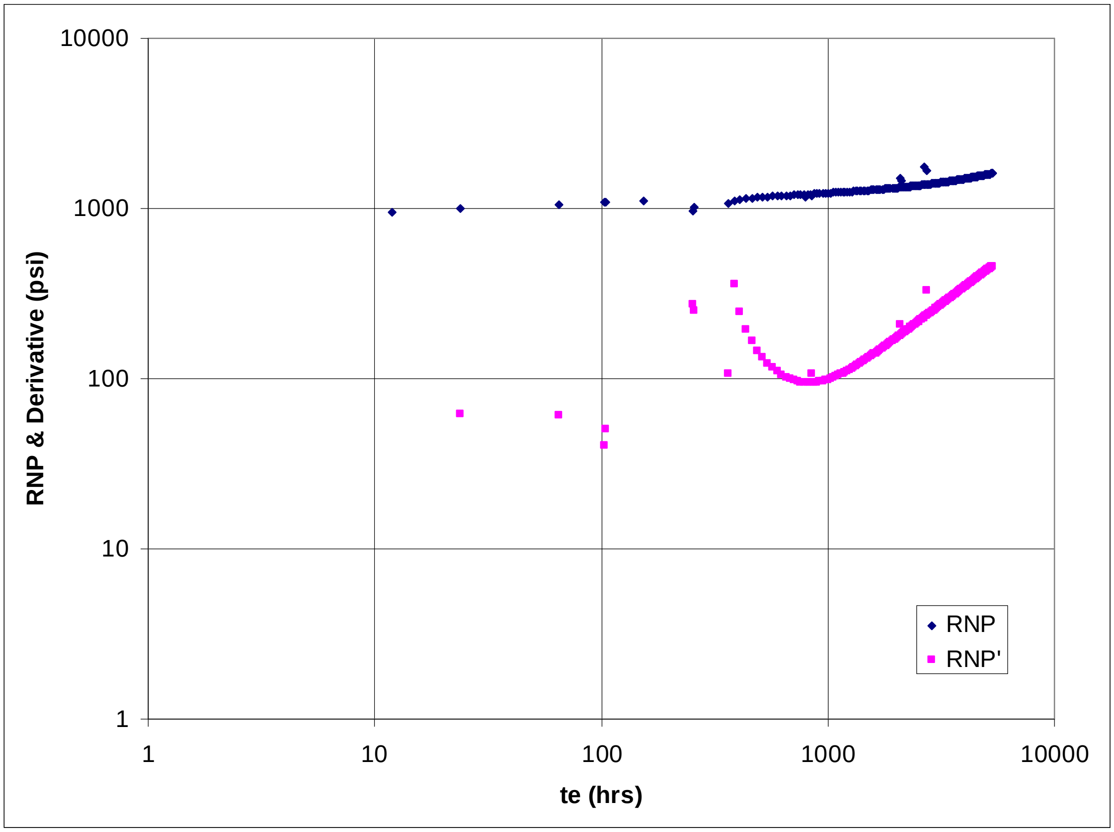

Figure 4.4: PDA Plot with Data Acquired Daily

The data processing technique was applied to the RNP and its derivative in Figure 4.3 to remove these artifacts from the log-log plots. The resulting plot is shown in Figure 4.5 along with a model for the entire virtual drawdown transient.

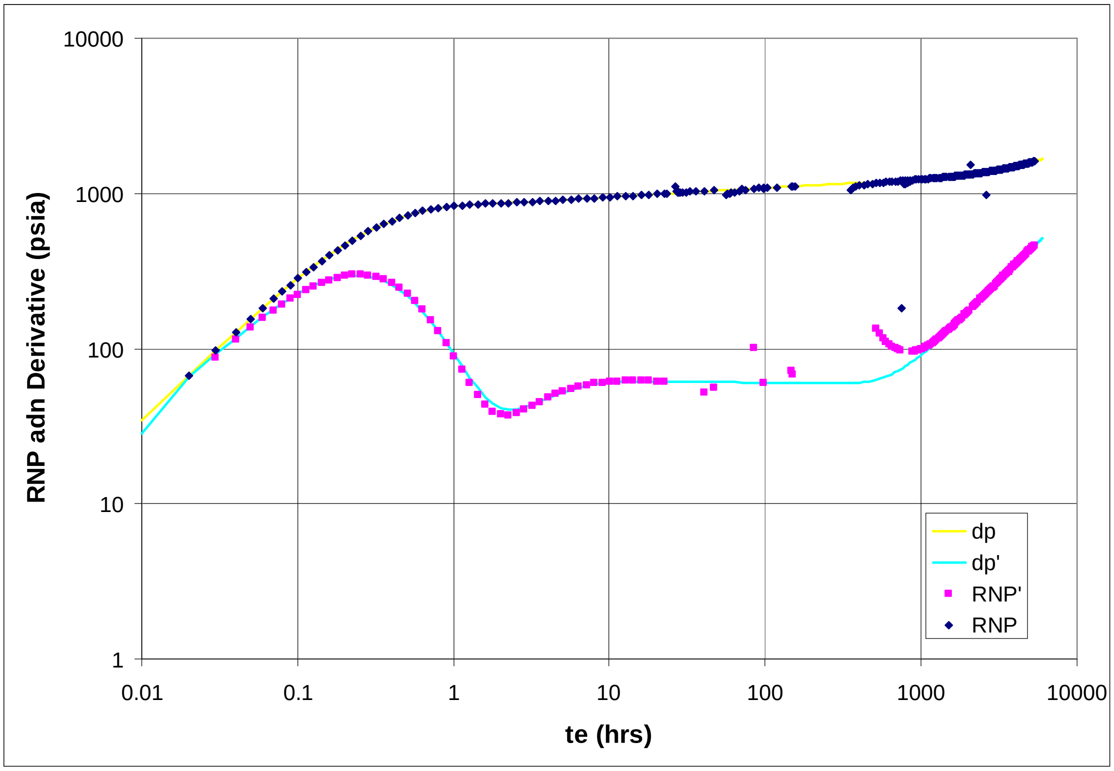

Figure 4.5: PDA Plot with Data Processing Techniques Applied

Both PDA and PTA data are now combined and plotted in a single graph in Figure 4.6.

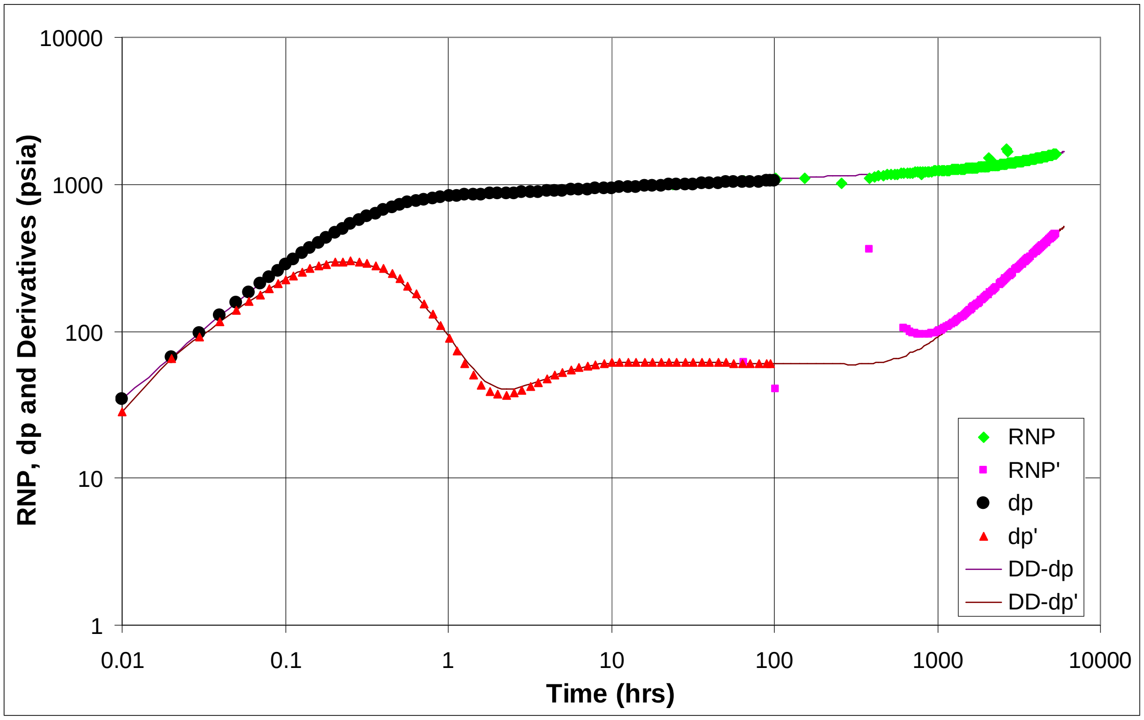

Figure 4.6: The Combined Plot

This is a simple case shown simply to illustrate how the techniques work. The production schedule in this case is unlike real/field production data as will be seen later because with the simulated case, we have long constant rate drawdowns which is not characteristic of field data.

4.3 Example 2: China Well

In Example 2, pressure and rate data for the PDA are surface measurements collected at the wellhead. Data were collected on a daily basis and reservoir and well properties were obtained from well files.

The following reservoir and fluid data were extracted from well files.

p_i = 8553 psia ϕ = 0.06

h = 42.6509 ft. μ = 3.83 cp

β_o = 1.0 rb/STB $c_t = 1.06869 * 10^{-5}$ $psia^{-1}$

r_w = 0.244751 ft.

Analysis of the production history in Figure 4.7 shows two build-ups early in the life of the well, the longer of which well test analysis will be performed on as illustrated in Figure 4.8.

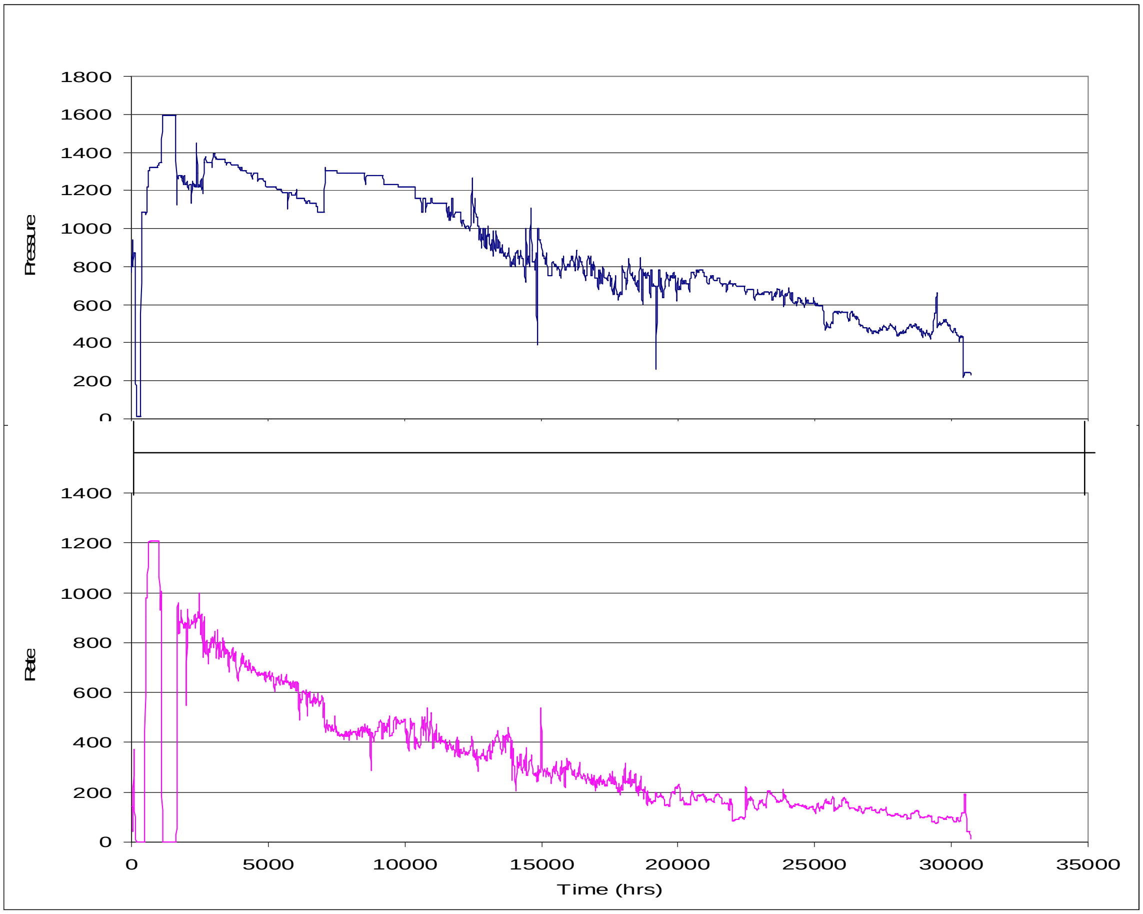

Figure 4.7: Production History Plot for Example 2

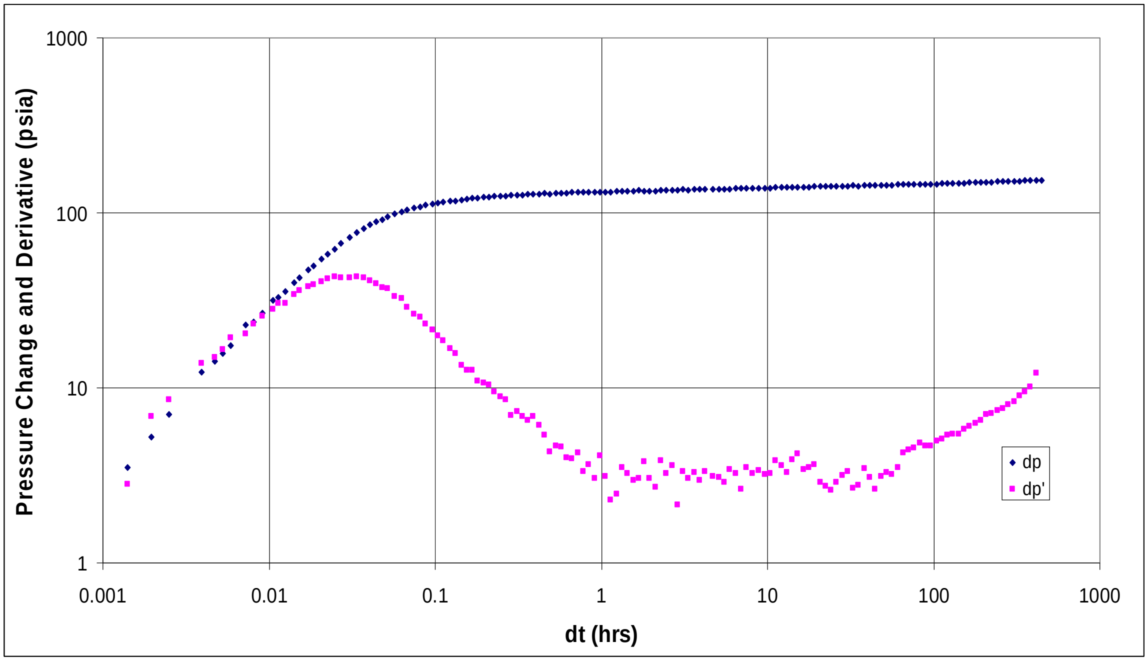

Figure 4.8: PTA Plot for Example 2

Figures 4.9 and 4.10 are the PDA plots for the well, with the data processing techniques applied to the computed points to yield the latter. The shaded region in Figure 4.9 shows the portions of the computed data to be truncated. As discussed earlier, these points are artifacts from the t_e computation, and will not be used in the analysis.

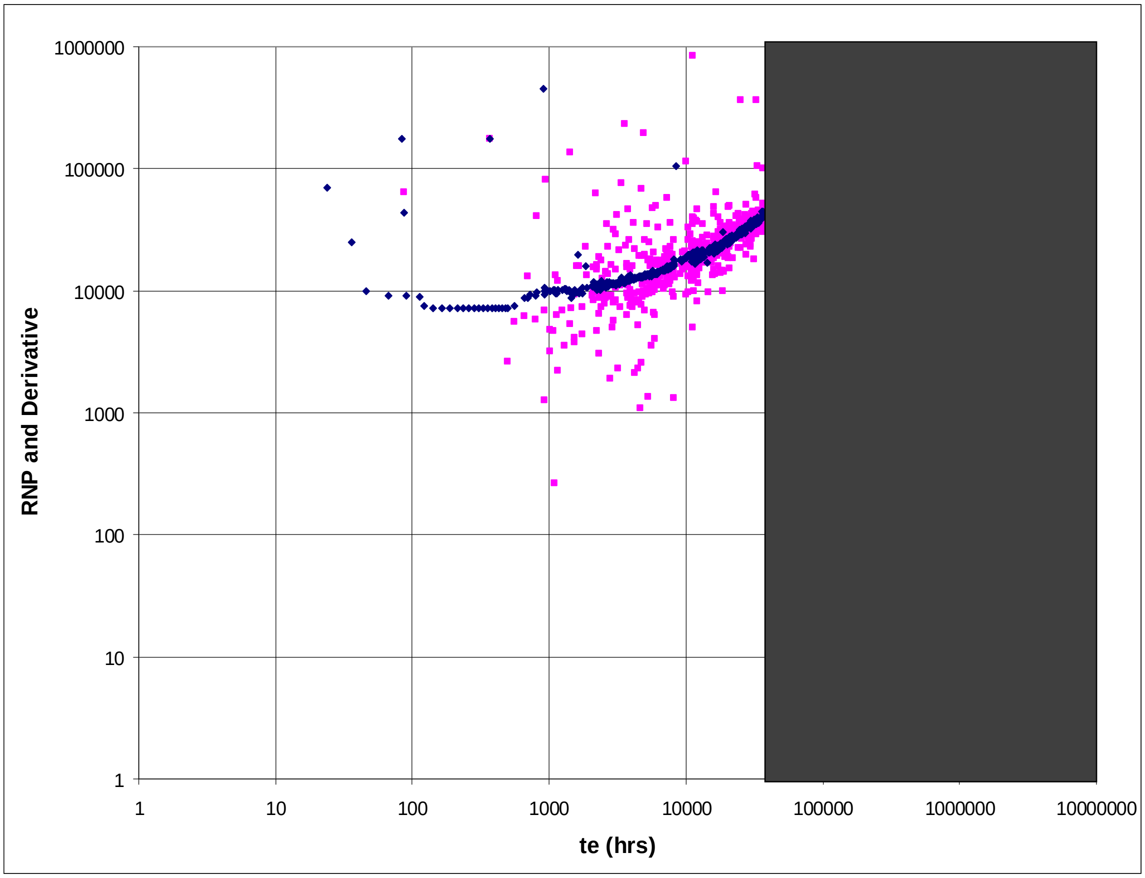

Figure 4.9: PDA Plot for Example 2

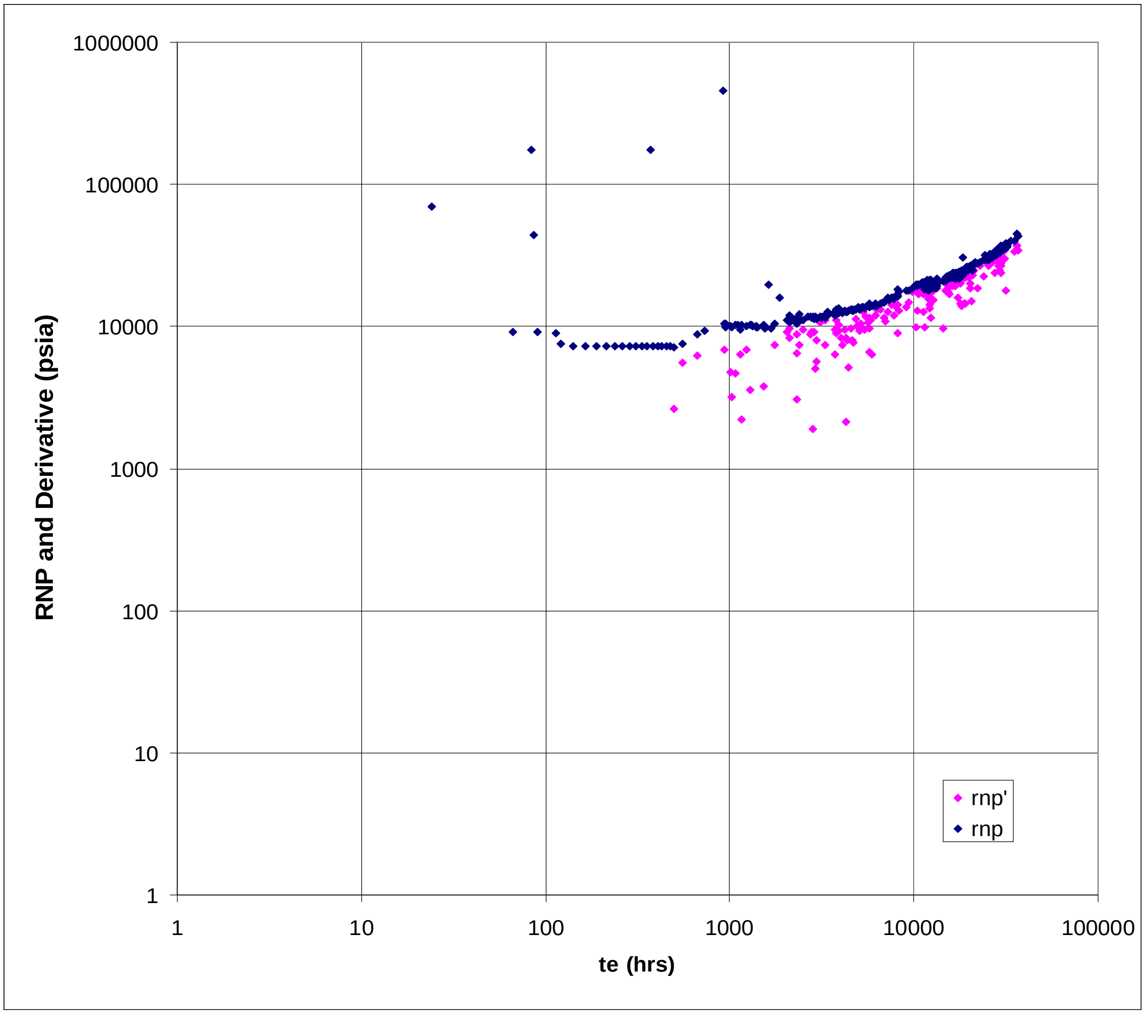

Figure 4.10: Data Processing Applied to Figure 4.9

Figure 4.11 is a combination of the PTA and PTA plots on a single diagnostic plot. There is an obvious misalignment between the PTA and PDA plots. A close examination of the production history showed that the last production rate (1201 bpd) was used for the build-up analysis. Actually, the rate before the longest build-up found in the production history was only 22 bpd. When this rate is used to normalize the RNP response, the misalignment is corrected as in Figure 4.12. Correcting the error in the build-up flow rate resulted in a much more realistic interpretation for the build-up data that is extended to the entire well drainage area via the combined build-up and RNP analysis.

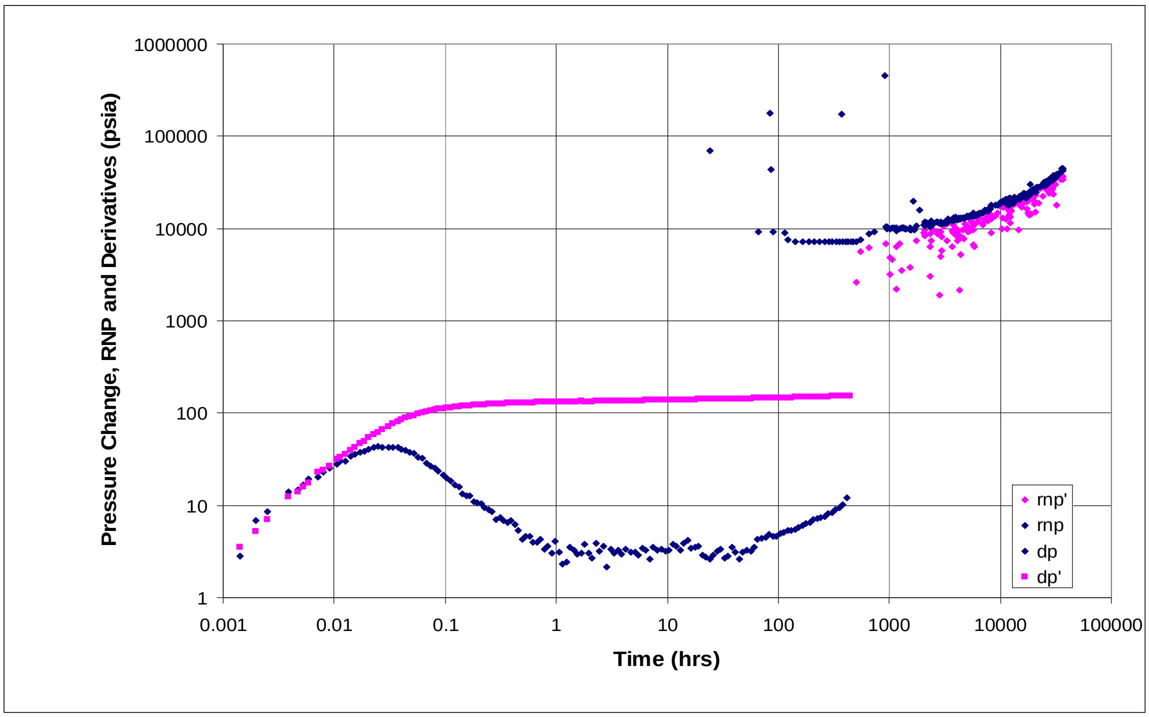

Figure 4.11: Combination Plot for Example 2

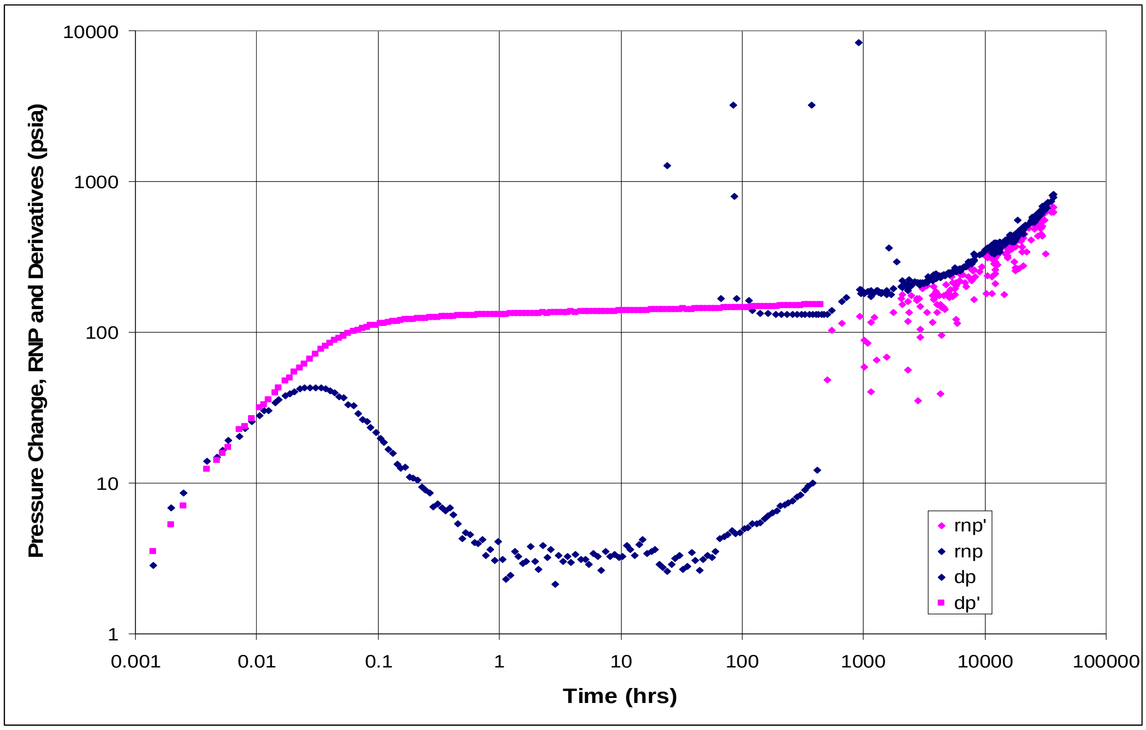

Figure 4.12: Ideal Combination Plot

By combining the analysis (PTA &PDA) and running a model for the entire virtual drawdown through it as in Figure 4.13, we discover flaws in the build-up. We see that model results match distances from reservoir maps, permeability is much smaller (and reasonable) and consistent with other/external information.

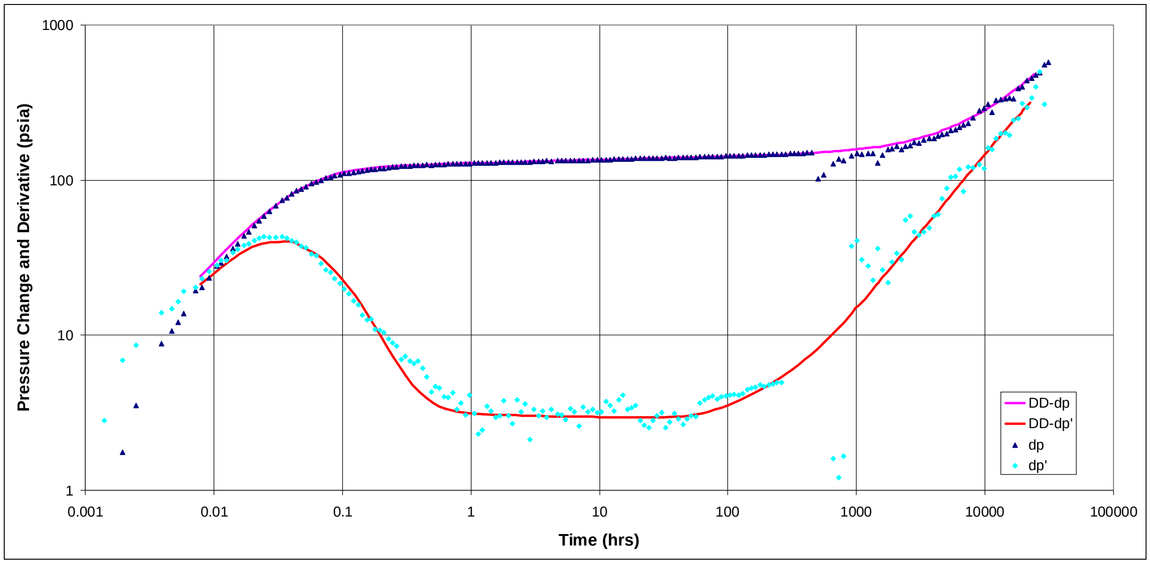

Figure 4.13: Combination Plot with Model for Virtual Drawdown

4.4 Example 3: Gulf of Mexico Well

In this example, pressure and rate data are obtained from a permanent downhole gauge located in the wellbore approximately 300 feet above the productive zone and a multiphase flowmeter located at the subsea wellhead, with pressure and rates collected simultaneously at very high frequencies. Analysis of the production history plot shows several build-ups (planned and unplanned) between drawdown durations. Reservoir and fluid properties are obtained from the operators.

The following reservoir and fluid data were extracted from well files.

$p_i = 12674$ psia	$\phi = 0.3013$
$h = 100$ ft.	$\mu = 0.64$ cp
$\beta_o = 1.5$ rb/STB	$c_t = 1.622 * 10^{-5}$ psia^{-1}
$r_w = 0.3542$ ft.	

Figure 4.14 shows the history plot for this well's production.

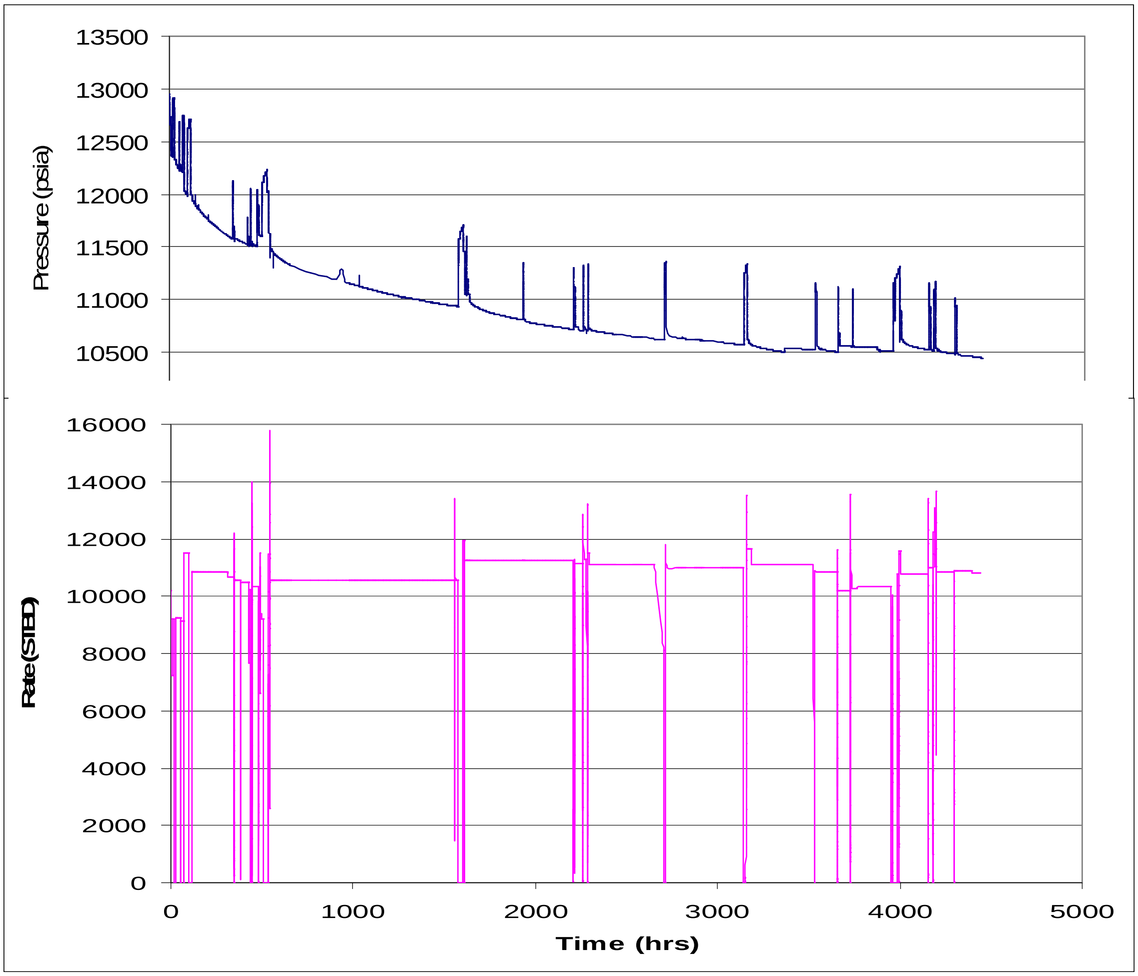

Figure 4.14: History Plot for Example 3

A review of the history plot shows early times when pressures were obtained with no corresponding rates. Regions such as this and some others with uncorrelated pressures and rates were deleted and not used in the analysis.

Exported pressures and rates were used to calculate plot variables. Just as was performed in Examples 1 and 2, Figures 4.15 shows a 24-hour build-up with the pressure change and its derivative plotted against shut-in time.

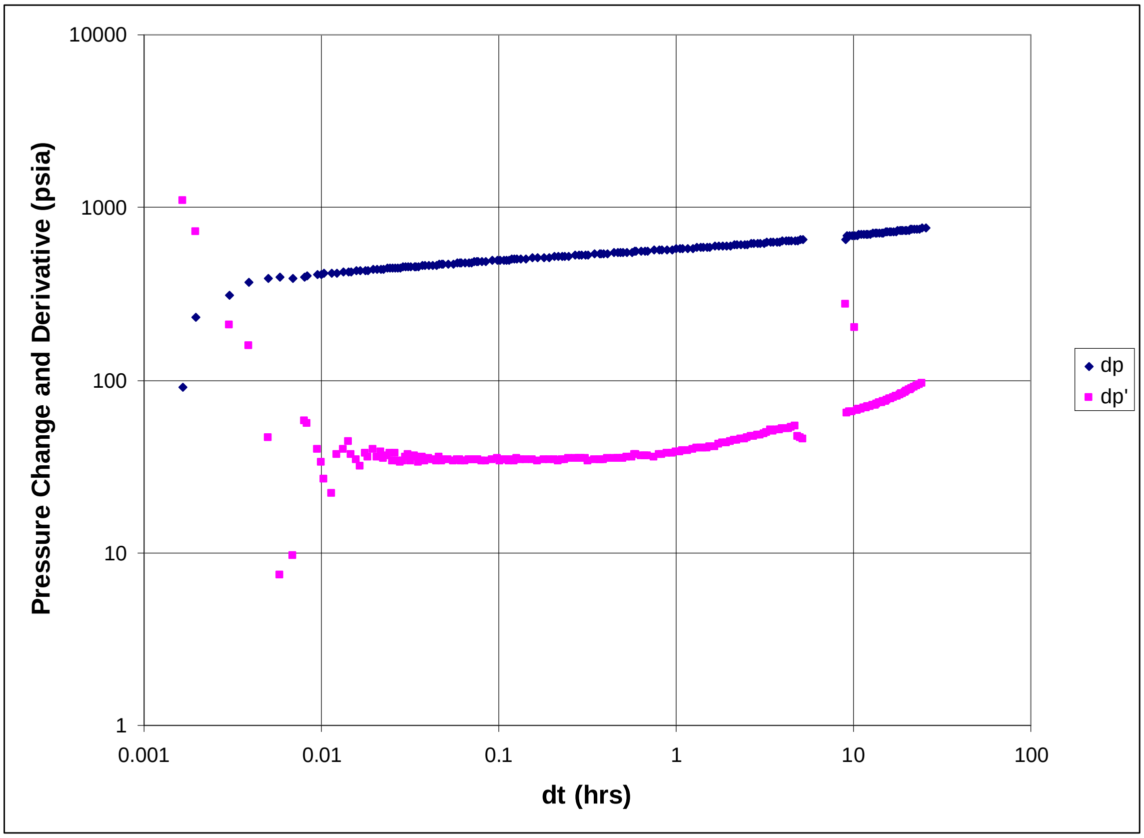

Figure 4.15: PTA Plot of 24-hr Build-Up

Figure 4.16 is the PDA plot of the entire production history without any of the data processing techniques applied. These results are atypical of field production data because there is rarely production data for times less than one day. The high production data rate causes artifacts like those shown in the simulated example. A lot of the artifact in this data is attributed to the continuous and abundant rate variations in this data set. The previously discussed effects of the material balance time are also evident with unusually high values of t_e on the plot. The shaded region in the graph indicates computed data that will be removed from subsequent analysis.

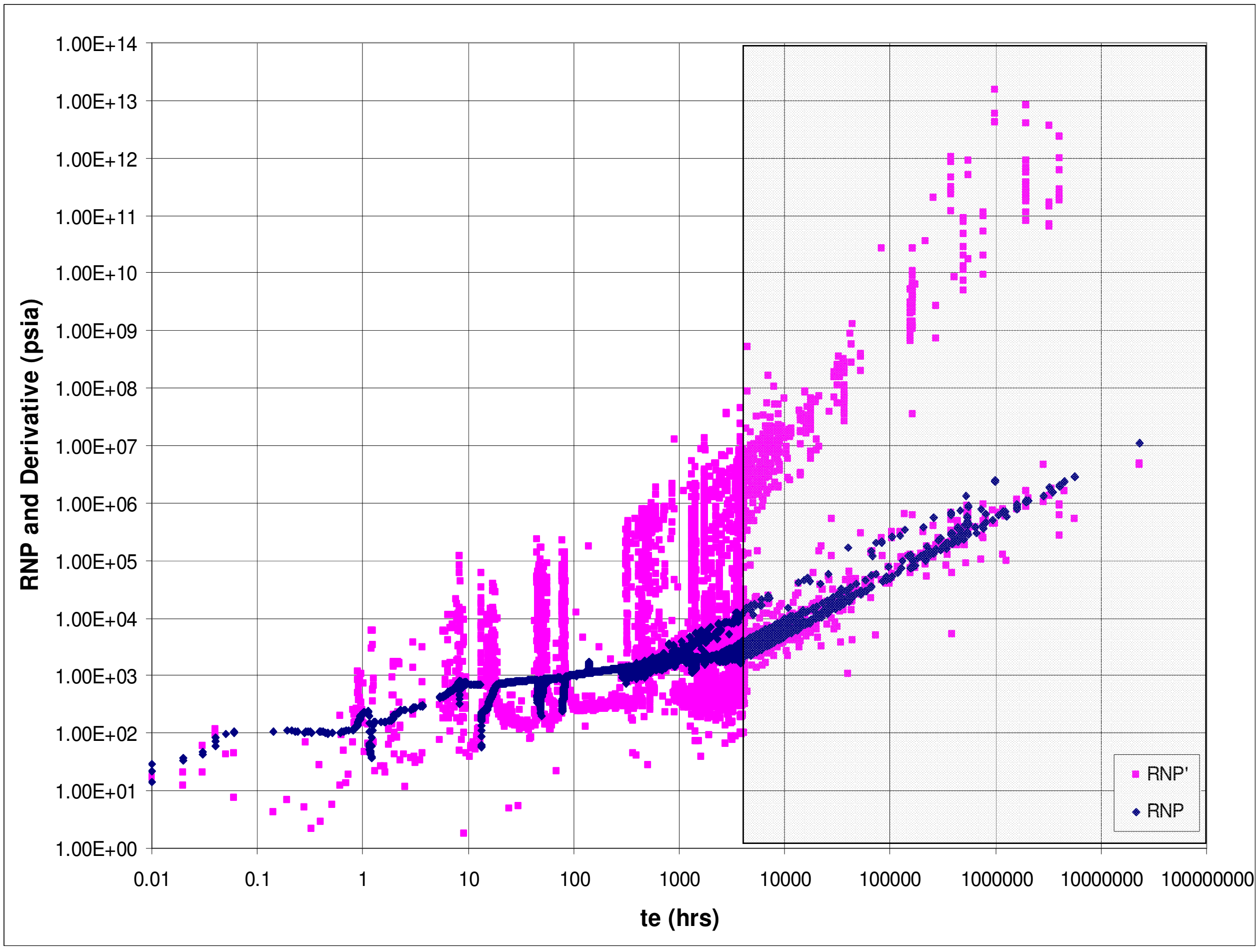

Figure 4.16: PDA Plot for Example 3 - All the Data

Figure 4.17 illustrates the plot in Figure 4.16 with most of the noise and artifacts removed, to reveal the actual trends in the data. The t_e scale was also truncated to the actual producing time.

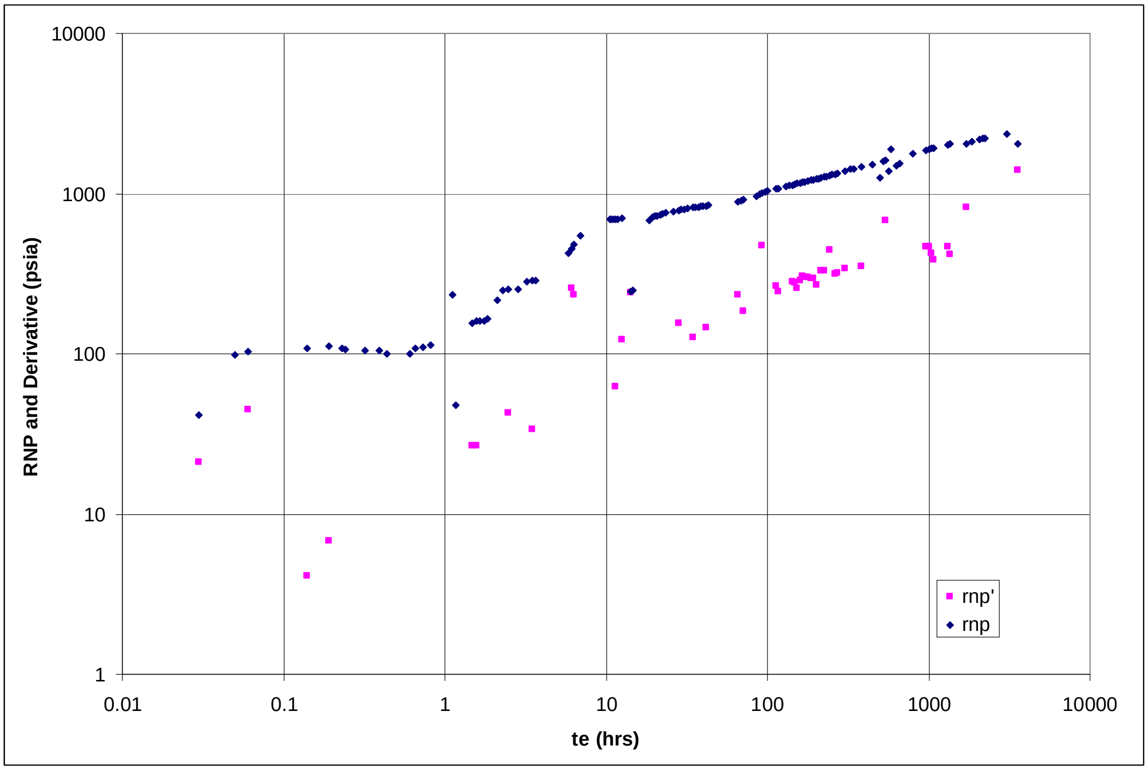

Figure 4.17: PDA Plot for Example 3 - Artifacts and Noise Removed

Both of Figures 4.15 and 4.17 are combined on a single plot to yield Figure 4.18 – the combined plot technique and continuous model signatures for the entire production history of this well.

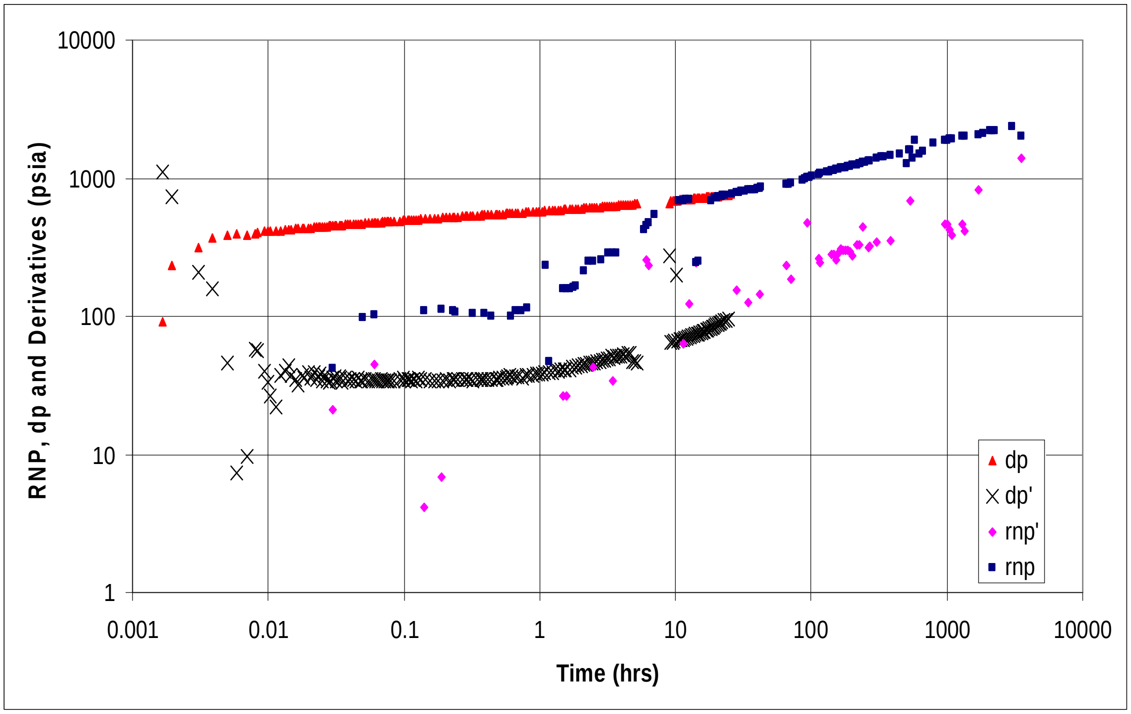

Figure 4.18: Combined Plot for Example 3

The results are astonishing. Instead of either steady state or pseudosteady state behavior, as indicated previously by Ehlig-Economides, et al.[20], the late time data show a clear ¼ slope, normally considered an indication of bilinear flow. The model for this response suggested by Ehlig-Economides, et al, assumes that the oil reservoir acts like an elongated flow channel supported by linear flow long the reservoir length from an aquifer. The model from Ref. 20 is shown in Figure. 4.19.

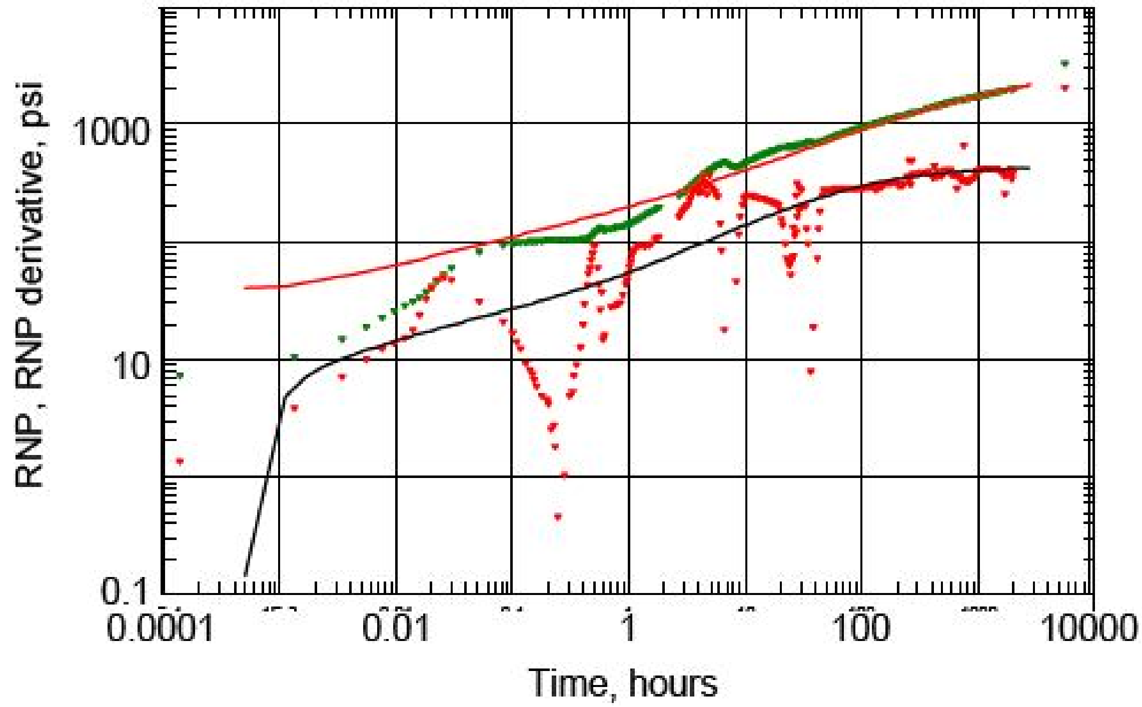

Figure 4.19: Model Match with RNP and Derivative (from Ehlig-Economides, et al.[20])

A close examination of the flow regime trends for our combined response suggests another interpretation. As illustrated in Figure 4.20, from about 1 to 10 hours, the buildup response shows a ¼ slope like that seen again in late time from about 100 hours on. The cause for the rise between the two apparent bilinear flow regimes may be the far boundary of the oil reservoir, which may extend in the aquifer as well.

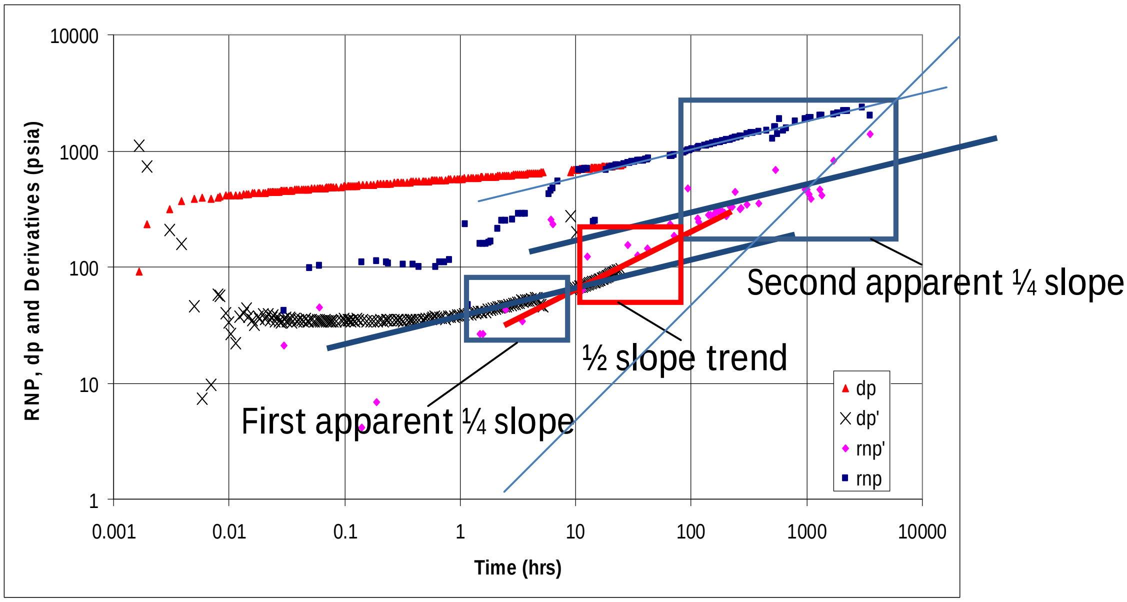

Figure 4.20: Combined Plot for Example 3 Showing Characteristic Trends

Even after nearly 5000 hours of flow, the pseudosteady state flow regime has not been reached. This late time transient may be caused by pressure support from the infinite acting aquifer.

CHAPTER V

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Summary

This study presents a comprehensive approach for the diagnosis of long term production data for reservoir characterization. We have discussed existing diagnostic methods for production data analyses, describing their plot variables and characteristic signatures. We described in detail the development and use of the rate normalized pressure (RNP) and gave reasons as to why it is our preferred choice used in developing our analysis technique.

The application of the new analysis method was described and major interpretation and presentation issues were treated. We have employed one simulated case and two field cases as a mechanism to demonstrate how this new technique works. Each case was analyzed using the total production history of the well. In particular, we used the set of procedures given in the *Stepwise Analysis Procedure* section in the previous chapter.

The most challenging aspects of this work include the data review stage – determining what data portions to be used in the computation and distinguishing possible reservoir signatures from artifacts in the plot presentation.

5.2 Conclusions

The following conclusions were derived from this study.

1. The use and application of this technique can enable a full description of the well drainage area due to the long effective test duration that includes the entire production history.
2. We have successfully applied this technique to total production histories, combining PTA and PDA on a diagnostic plot to fully characterize the reservoir from early time through the pseudo-steady state flow regimes in one field case and to reveal an infinite acting aquifer in the other.
3. The application of this technique to accurately measured production rate and pressure data should yield a robust and competent interpretation/analysis, with results comparable to estimates obtained from the analysis of PTA alone, but of much longer duration.
4. This technique is easy to use and conventional interpretation techniques apply.
5. The analysis of production data is uniquely tied to the quality and quantity of data. Poor quality data generates noise in the technique and high frequency data yield artifacts.
6. In the analysis of production data, care must be taken to identify artifact and noise in the computed points and to remove these redundant points from the plot presentation.

7. Artifacts are caused by the compression of rate transient events on the logarithm scale, and data processing algorithms have been shown to remove these redundant data points.

8. The technique requires normalization of the RNP. This is a user-dependent function and we recommend the use of the last rate before the selected PTA shut-in period.

9. The use of this technique will save interpretation/analysis time and thus, money. It will also help unify interpretations that today may be produced independently by different interpreters.

10. The production history is an important element of the analysis process and must always be taken into account especially to quality check rates and corresponding pressures at any time.

11. A mismatch/misalignment of the PTA and PDA on the plot may not be a sign of eminent failure in the technique/ analysis sequence. Rather, any mismatches should be thoroughly investigated. These mismatches may be traced to the use of a wrong normalization rate, or unknown or unreported events in the well completion history.

5.3 Recommendations for Future Work

The technique developed in this work is very good for reservoir characterization. The technique is relatively simple to use and should be applicable to a wide range of well and reservoir complexities. This study prescribes a logical and stepwise procedure for the analysis of production data and for future work, we recommend the following:

1. Analysts should always perform the data review steps carefully
2. Continuous application of the technique to varying well and reservoir complexities.
3. Automation of the technique to incorporate geologic models for commercial software use.
4. Continued efforts in developing efficient data processing techniques to improve/fine-out plot presentation.

NOMENCLATURE

Variables

B	= Formation Volume factor, RB/STB
b_{pss}	= Pseudosteady state constant, dimensionless
C_A	= Dietz shape factor, dimensionless
c_t	= Total system compressibility, psi-1
h	= Pay thickness, ft
k	= permeability, md
N	= Initial oil in place, STB
N_p	= Cumulative oil production, STB
p-	= Average reservoir pressure, psi
p	= Pressure, psi
p_i	= Initial reservoir pressure, psi
p_{wf}	= Well flowing pressure, psi
Δp	= Pressure change, psi
q_d	= Dimensionless rate
q_{Dd}	= Decline curve dimensionless rate
Q_o	= Cumulative oil produced, STB
q_o	= Instantaneous oil flow rate, STB/D
$q(t)$	= Surface flow rate at time t, STB/D
r_e	= Reservoir outer boundary radius, ft

r_w = Wellbore radius, ft

t = Time, hr

t_{Dd} = Decline curve dimensionless time

t_D = Dimensionless time

t_e = material balance time, hr

Δt = Shut-in time, hr

t_{cp} = Equivalent pressure time as defined by McCray[33]

t_{cr} = Equivalent rate time as defined by McCray[33]

Greek Symbols

μ = Viscosity, cp

ϕ = Porosity, fraction

τ = Dummy variable of integration

Subscripts

o = Oil

g = Gas

pss = Pseudosteady state

wf = Well flowing

i = Initial

p = Production

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